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Bulletin of the Museum of Comparative Zoölogy

AT HARVARD COLLEGE.

Vol. XLIX.

GEOLOGICAL SERIES, Vol. VIII, No. 1.

GLACIATION OF THE SAWATCH RANGE, COLORADO.

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By W. M. Davis.

With One Plate.

CAMBRIDGE, MASS., U. S. A.:

PRINTED FOR THE MUSEUM.

December, 1905.

Reports on the Scientific Results of the Expedition to the Eastern Tropical Pacific, in charge of Alexander Agassiz, by the U. S. Fish Commission Steamer "Albatross," from October, 1904, to March, 1905, Lieutenant Commander L. M. Garrett, U. S. N., Commanding, published or in preparation: —

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H. LUDWIG. The Holothurians.
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H. R. SIMROTH. The Pteropods and Heteropods.
TH. STUDER. The Alcyonaria.
T. W. VAUGHAN. The Corals.
R. WOLTERECK. The Amphipods.
W. McM. WOODWORTH. The Annelids.

[1] Bull. M. C. Z., Vol. XLVI., No. 4, April, 1905, 22 pp.
[2] Bull. M. C. Z., Vol. XLVI., No. 6, July, 1905, 4 pp., 1 pl.
[3] Bull. M. C. Z., Vol. XLVI., No. 9, September, 1905, 5 pp., 1 pl.

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DECEMBER, 1905.

No. 1.— *Glaciation of the Sawatch Range, Colorado.*

By W. M. Davis.

The accompanying sketches of La Plata peak and the valleys of the Sawatch range in the Rocky mountains of Colorado emphasize better than long descriptions the essential features of a glaciated mountain mass. The Sawatch range lies west of the upper Arkansas valley, and includes the three college peaks, Mts. Harvard, Yale, and Princeton, the first two of which were ascended by a small party led by Prof. J. D. Whitney in 1869, when I accompanied him as a student. A number of the summits exceed 14,000 feet by several hundreds; Mt. Harvard (14,375′) was for several years considered the highest of the Rocky mountains in the United States, until Blanca peak (14,390′) was given that rank; and now Mt. Elbert, in the Sawatch range a score of miles north of Mt. Harvard, is placed first in the list, with an altitude of 14,436 feet.

The summer of 1904 gave me an opportunity of making a brief visit, with Prof. L. G. Westgate as a companion, to that part of the Sawatch range near Twin Lakes on Lake creek, which comes from a fine glaciated valley between Mts. Elbert and La Plata, and flows eastward into the Arkansas river. The village of Twin Lakes (called Dayton on the Leadville map sheet) is a picturesque and attractive center for excursions, easily reached by stage from Granite station on the Rio Grande Western and the Colorado Midland railroads. Professor Westgate returned here after our joint excursion to Utah, and continued for a month the studies that we had begun together; his report on the district, with special reference to the two or more epochs of glaciation there recorded, is published in the *Journal of Geology*.

The general view of La Plata peak, figure 1, looking southwest, is taken from one of the southwest spurs of Mt. Elbert, at a height of about 13,000 feet. A photographic view from about the same point is given in the Plate (A). The broadly open valley or trough of the Lake creek glacier lies beneath the foreground spurs, and its farther slopes truncate several spurs of the La Plata mass. Crystal lake gulch opens its well rounded floor sharply on the south wall of the larger and deeper trough of Lake creek, the difference of level of the two trough floors being about 800 feet, as determined by aneroid measurement. The notable features of the view, besides the clearly defined hanging valley or trough, are: — the sharp summits of La

Plata mountain and its acutely serrated spurs, the rolling or moutonnée surface of the broad cirque floor at the head of the hanging valley, and the truncated spurs on the sides of the two troughs.

The larger trough truncates the large spurs in a liberal fashion, shown more clearly in figure 2, which was drawn from a knob on the north side of Lake creek trough, somewhat east of the hanging valley. A photographic view of the same spurs is given in the Plate (B), from the high spur of Mt. Elbert. The body of the spurs here appear to be in the main of preglacial origin, modified by ordinary erosion during the glacial period, for through most of their length

FIG. 1.—La Plata peak, with Crystal lake gulch hanging over the deep trough of Lake creek; looking southwest.

they correspond in essential features to the spurs of the non-glaciated mountains thereabouts. Features of this kind will be called "normal." While the normal spurs of non-glaciated mountains gradually descend into maturely open valleys, the spurs here sketched are truncated by the south wall of the broad Lake creek trough in the most significant fashion.

The smaller trough of Crystal lake gulch truncates the smaller spurs which descend from a sharp ridge or arête on the west, and similar but less pronounced spurs on the eastern slope of the trough, as shown in figure 3. It should be said, however, that

the sketches exaggerate the regularity of these features, and present them only in diagrammatic fashion; but they nevertheless are believed to represent true and systematic relations. The small spurs are thought to be the result of accelerated subaerial erosion during the glacial period, a consequence of the widening and deepening of the trough below them; in any case, the sharp ridge and the little spurs with their ragged terminal facets have no likeness to the rounded, graded, subdued spurs of the neighboring non-glaciated lower mountains. The western side of the ridge descends into another trough, which must also have been occupied by a good-sized branch of the Twin lakes glacier; and the sharpness of the ridge is therefore to be

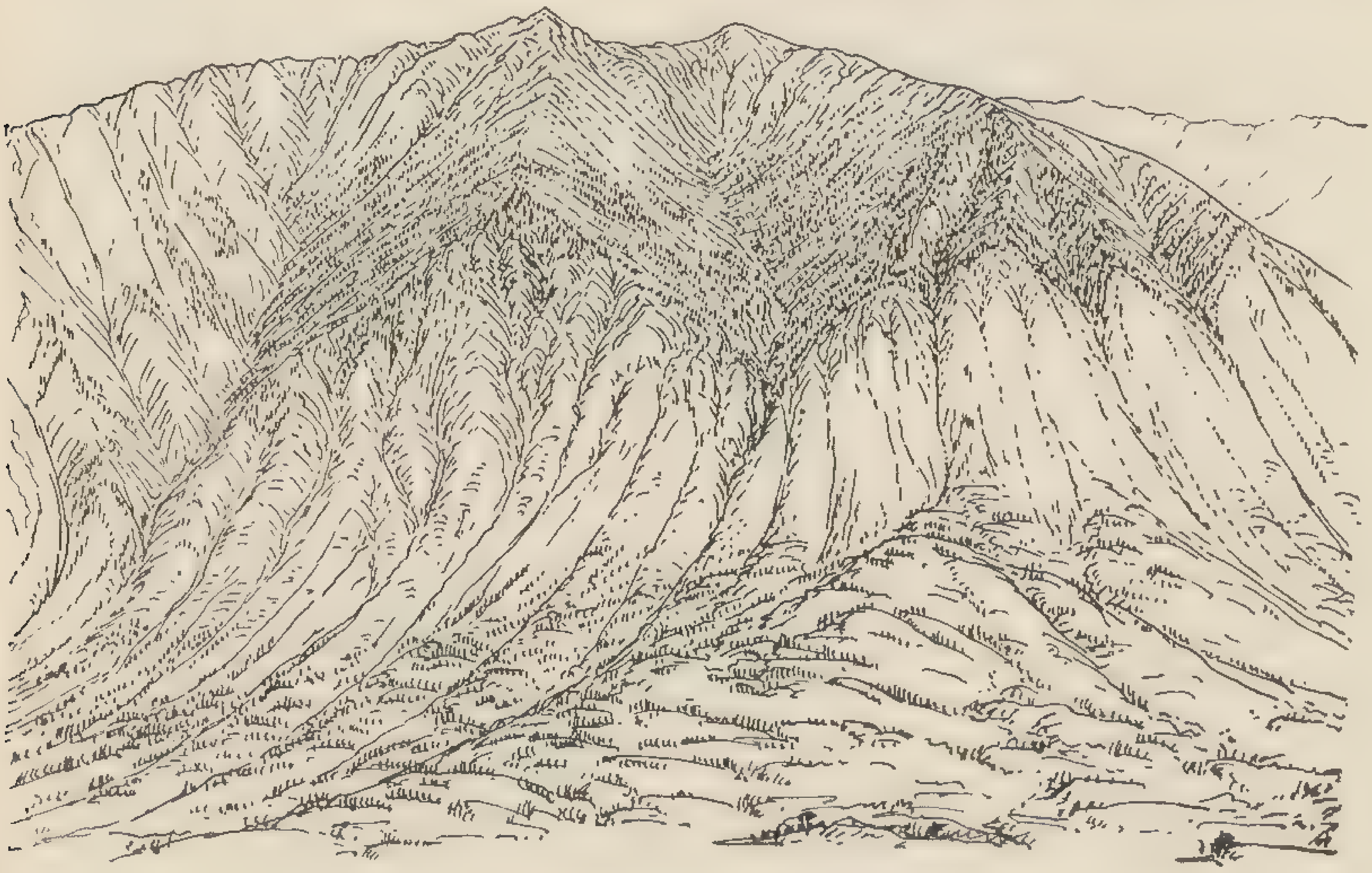

FIG. 2.— Truncated spurs on the south side of Lake creek trough.

attributed to its attack by glacial sapping on both sides. In the same way the sharpness of La Plata peak is to be attributed to glacial sapping in the cirque-head walls on all sides; and in this respect the sharpness of La Plata presents a most instructive contrast to the domed summit of Elbert, on whose higher shoulders a number of small glacial cirques were excavated, but not so far as to consume all of the normal summit form. Just as any statue must be smaller than the block from which it is carved, so the sharpened peak and spurs of La Plata (14,342′) must today be smaller and lower than the normal preglacial mass, whose form may have imitated and whose altitude may then have exceeded that of Elbert (14,424′).

Figure 3 is another view of the same hanging valley, drawn from a point on the north side of Lake creek trough. Here the spur on the east side of the hanging valley has not a very sharp ridge, because the next eastern valley, Galena gulch, was not strongly glaciated. There is much rock-slide material on the floor of the hanging valley, beneath the "spurlets" and "ravinettes" of its sharply carved walls.

The trough of Lake creek glacier has in general a broadly open catenary curve for its cross section, as indicated in figure 4, but there are many subordinate departures from the perfect development of

FIG. 3.—Crystal lake gulch hanging over the deep trough of Lake creek; looking south.

this type form. The trough is encumbered with many rocky ledges and knobs, which seem to be of formidable size while one is clambering over them, especially on their down-valley side where the plucking action of the glacier made rough work of the jointed granite; while the up-valley sides of the ledges are generally scoured to more rounded forms. This suggests that the two sides of such residual glaciated ledges should be called scoured and plucked, instead of stoss and lee; for the so-called lee side is by no means exempt, in such cases as are here described, from strong glacial erosion. Yet

large as the ledges and knobs seem when one is on them, they sink to a subordinate rank when viewed from the higher mountain spurs. The knobs and ledges may be taken to be so many unfinished pieces of work, which would have been more completely scoured away had the glacial action lasted longer. It is therefore desirable to describe glaciated troughs in terms of the degree of advancement that they reached while under glacial treatment. The faces of some of the larger residual knobs on the sides of the main trough showed well marked traces of nearly horizontal down-valley scouring and carving; that is, they bear the marks of having been shaped in accordance with the movement of the heavy glacier that once occupied

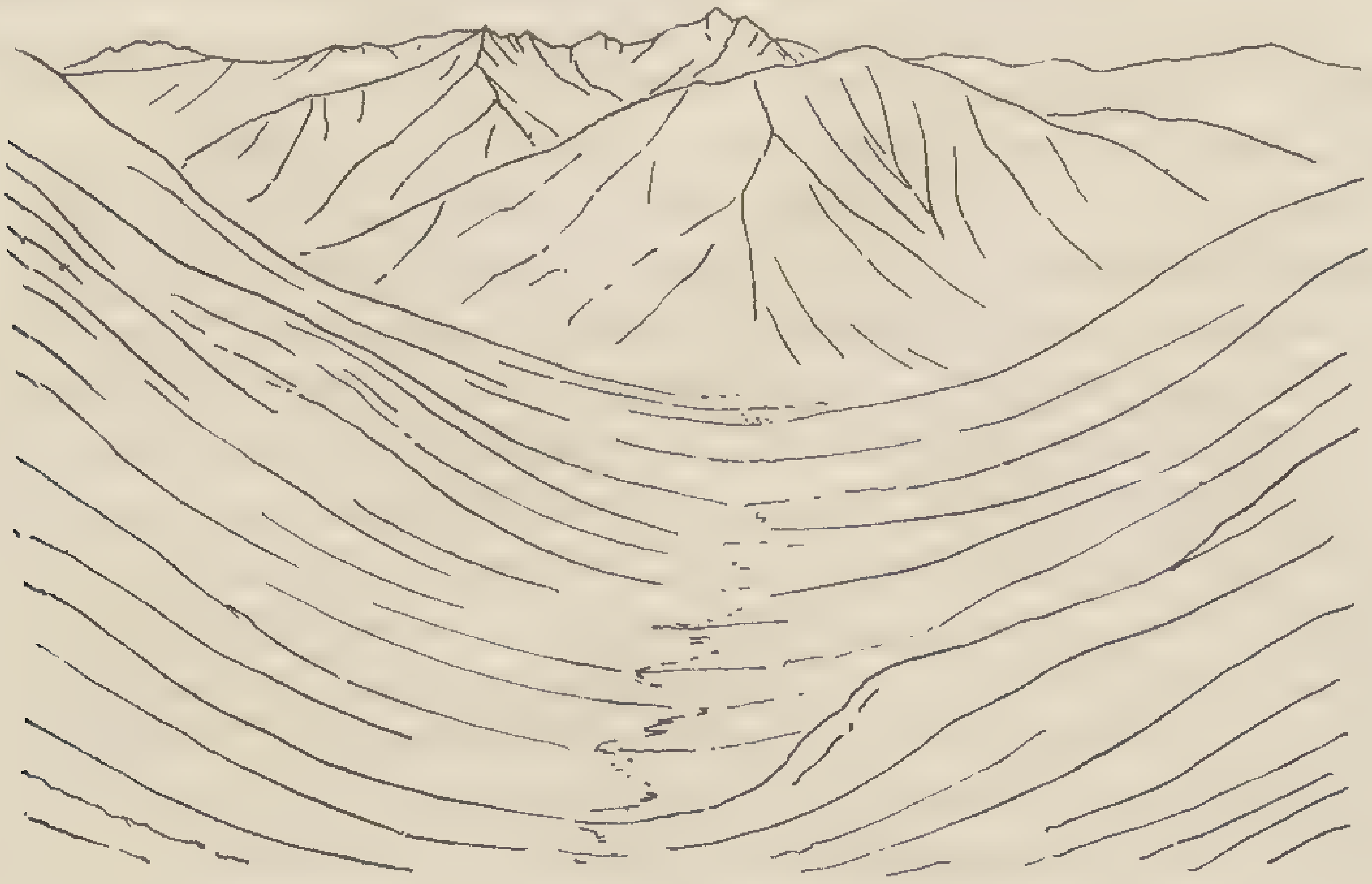

FIG. 4.— The glacial trough of Lake creek; looking west.

the trough, and not of having been carved by normal erosive processes which are now acting locally down the slope of the trough side. Features of the same kind are known on the sides of the Norwegian fiords; their analogy to the normal down-stream marks on the banks or sides of a water-stream channel have been pointed out.

The openness of the Lake creek trough, figure 4, as seen from a high spur over its eastern end, and the absence of forward reaching spurs with overlapping ends, suggest the late maturity of a normally eroded valley; but the rocky floor of the main trough is not flat, as it would be in the late stage of a normal valley; the slender stream that now drains the trough has numerous rapids among the residual

ledges of the trough; and the rapids increase in fall as the stream passes certain breaks or steps in the trough bed, thus departing very clearly in several ways from the well-graded flow of a stream in a normally mature valley. The lower end of the southeasternmost spur of Mt. Elbert is all hacked and torn where it was wrapped around by the Lake creek glacier about a mile southwest from the village of Twin Lakes; the spur, therefore, shows a fine piece of well advanced but not well finished glacial erosion in the rough ledges and the high cliffs that here truncate the well graded slopes of its upper or superglacial parts.

All these features have an expression distinctly unlike those produced by normal processes. The hanging lateral valley or trough of Crystal lake gulch differs most conspicuously from a normal lateral valley in its lack of accordance with the main valley. The broad cirque head of the lateral valley is in strong constrast to the more delicate valley heads of the neighboring normally eroded, non-glaciated mountains. Just in what manner glacial erosion works to produce these systematically correlated abnormal features is not yet fully made out, but that they represent strong glacial modifications of normal preglacial forms is beyond question. As to the measure of such erosion, the depth of the main trough below the side trough may be taken as a fair minimum; for it is extremely improbable that the mouth of the hanging lateral can be today no deeper carved than the corresponding point in the preglacial side valley. A peculiar feature is seen in the ravining of the sides of the main trough by several small streams from gulches between the truncated spurs to a greater depth than by the stream of Crystal lake gulch. The latter has done very little work in cutting a notch in the lip of its hanging mouth; the former in several cases have ravines, of small size to be sure yet of relatively normal quality, eroded to depths that must be hundreds of feet lower than the upper limit of glacial scouring on the trough sides. Interglacial work is probably concerned here; but why it was not successful in ravining the mouth of the hanging valley is not clear. These questions I leave to Professor Westgate for solution.

A matter that still needs distinct statement in problems of this sort is that, in ascribing to glacial erosion the strong modification of preglacial forms above described, it is not to be implied that the processes of glacial erosion are fully understood. Sapping by temperature changes is believed to take place in the bergschrund around the head of a cirque; but the depth of the cirque beneath the névé surface

must often been much greater than the depth of the bergschrund. Scouring and plucking are effective processes, yet it is difficult to understand how they can have been so effective as to excavate great cirques and transform normal valleys into broad and overdeepened troughs, whose beds are far below the mouths of their hanging tributaries. The reason for accepting a large measure of glacial erosion is therefore not because a full understanding of the methods of glacial erosion has been gained, but, in our admittedly incomplete understanding of this process, because the forms that are found to be constantly associated with ancient glaciers in mountain ranges all over the world are on the one hand essentially beyond production by normal processes, and are on the other hand precisely like the

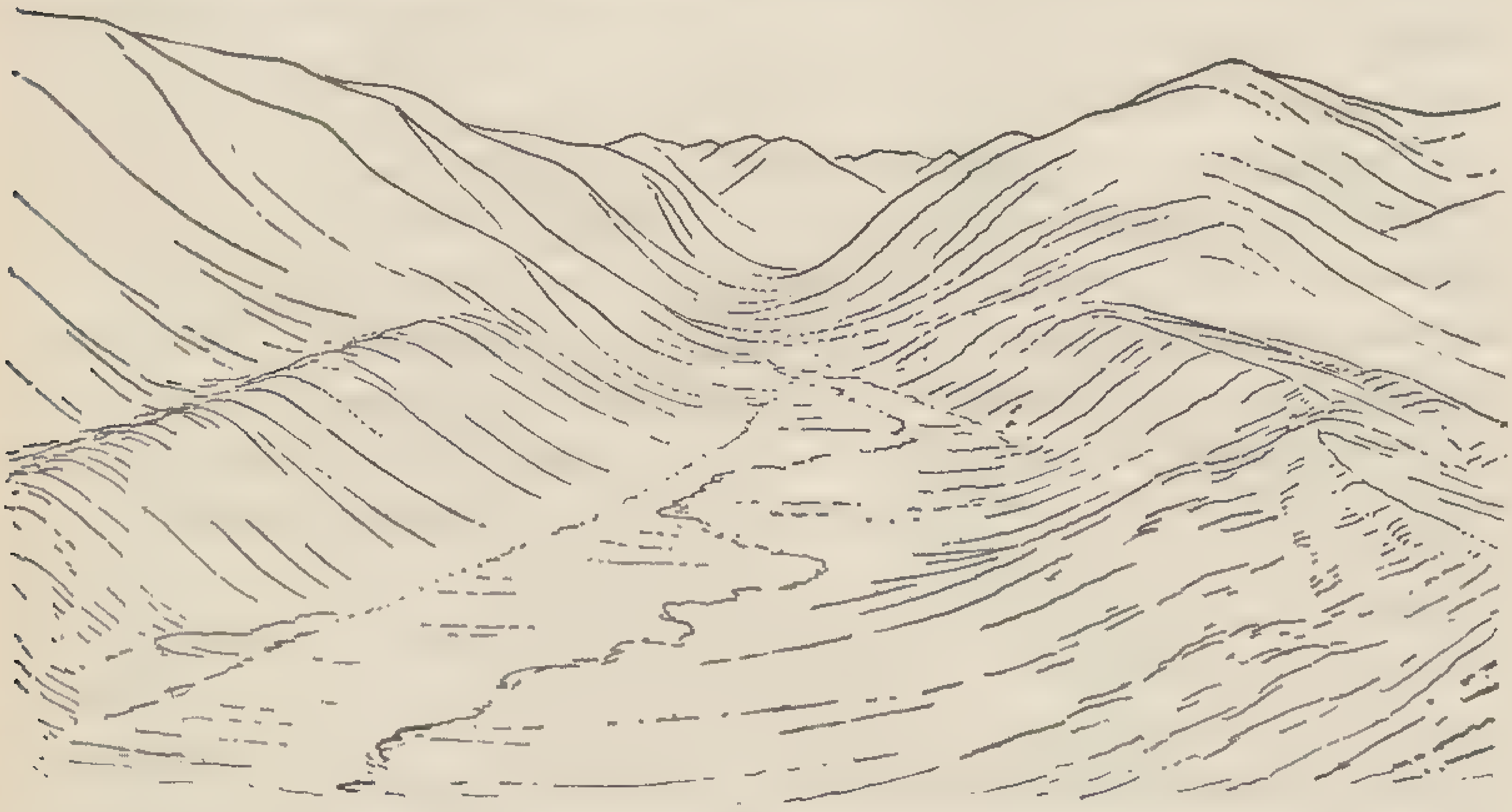

Fig. 5.— The glacial trough and moraines of Clear creek; looking west.

forms that glaciers might be expected to produce if they were active eroding agents. The contrasts of the two classes of forms have been frequently set fourth in recent years, and need not be again stated here; but the systematic association of the large-textured forms of apparently glacial origin in the glaciated valleys of the Sawatch range deserves to be better known than it is; and all the more because the forms of normally eroded valleys can be studied in the neighboring non-glaciated or less glaciated mountains, whose structure, height and history have in all other respects than glaciation been essentially the same as those of the strongly glaciated masses.

The trough of Clear creek, similar to that of Lake creek, but on the south of La Plata mountain, was seen from a high knob that rises on the east side of the Arkansas river, about three miles south of Granite. Here, as in the case of Lake creek, one may see the well formed trough with its catenary cross section — rather too steep on the sides in figure 5, — rising to the oversteepened slopes that truncate the mountain spurs on the north and south; while in the foreground two great lateral moraines stretch toward the river enclosing a meadow through which Clear creek meanders, instead of a pair of lakes, as is the case with the Twin lakes moraines. It is on account of the strong forward reach of these moraines from the glaciers of the Sawatch range on the west, while no glaciers were formed here on the lower range to the east, that the Arkansas has been locally pushed against the eastern side of its preglacial valley, where it has undercut and steepened the mountain bases, and incised a gorge in the granites. As the railroads here follow the gorge, the traveller for a time gains no general view. To the south of the gorge, the Arkansas valley is much less encroached upon by moraines from the western range, and its broad wash-plain stretches unbroken for miles together; yet here also the river flows near the base of the eastern range, probably because of the greater height of the western range and the consequently greater supply of waste from that side.

A fine view of the district south of the gorge is had from the trains of the Colorado Midland railroad, as they descend from the pass that leads from South park. Opposite the town of Buena Vista a grand view is offered of the Sawatch range, with Mt. Princeton (14,196′), a most shapely mass, in the center. A shallow, steeply inclined glaciated trough, heading in a small cirque and terminating in a morainic loop on the mountain flanks, is easily recognized on the northeast slope. The moraines that stretch out from the valley between Mts. Harvard and Yale are seen farther northwest. When I was in this region in 1869, a section of our party headed by Professors Whitney of Harvard and Brewer of Yale, crossed into the Arkansas valley from South park and ascended the Sawatch range, camping near the tree line for the two nights of the day on which we climbed Mt. Yale (14,187′). The following day was cloudy and wet and the Professors returned directly to the valley; but two of the younger members of the party were sent with barometer and compass across the deep valley between the peaks and up the northern mountain which was to be called Mt. Harvard. Occasional breaks in the clouds gave us glimpses of the

spurs that led to the main summit, and our cairn and record were found there by members of Hayden's party a year or two later. The descent to the valley camp was made in late afternoon and early evening, the latter part being a stumbling walk in the dark, through the trees that grew on the bouldery moraine at the mountain base.

North of Twin Lakes the Arkansas has not been impelled to cut a gorge; indeed here the main valley floor seems to have been temporarily converted into a lake by the morainic barriers near Granite. While the train crosses the broad meadows of the valley floor one has an excellent view of Mts. Elbert and Massive. Elbert has two normal valleys with graded hopper-like upper slopes that open like inverted half-cones to the rounded crests of their enclosing spurs. One of these normal valleys lies a mile or two northwest of the village of Twin Lakes and is marked with many zigzag trails, cut by prospectors: we descended this valley after our ascent of the high spur of Elbert from which figure 1 was drawn. The normally graded slopes of the inverted half-cone or hopper were noted at the time to be distinctly unlike the steepened and ungraded head cliffs of one of the small cirques that we had looked into from the rounded spur crest above it. The same contrast was recognized in the more distant view from the train, when the normal valleys in the northeast and southeast parts of the Elbert mass were clearly distinguished from the four cirque-headed valleys between them. At the same time the contrast between the sharpened peak of La Plata and the still rounded dome of Mt. Elbert was in mind, as one of the striking contrasts of glacial and normal erosion. Mt. Massive (14,424′), next north of Elbert, has at least six cirques on its eastern side. The distinctness of these features and the certainty with which they may be recognized as differing from valleys of normal sculpture, even at a distance of ten or twenty miles from a passing train, recalled my experience in the Tian Shan mountains a year earlier. On that journey cirques were recognized and sketched through field glasses at a distance of 30 or 40 miles.

It should be stated that the Leadville topographical map sheet of the U. S. Geological Survey, on a scale of 125,000, and with contours every 100 feet on the mountains, does little justice to the forms here described. The hanging lateral valley of Crystal lake gulch is shown by the contours to be only 300 feet, instead of 800 feet, over the floor of Lake creek trough. The truncation of the spurs, shown in figure 3, is poorly rendered on the map. The spurs about

Galena gulch are too slender in comparison with the trough floors between them; and it was strongly our impression that the contours were drawn too directly across the trough floors, making them flat-floored instead of round-floored. One reason for these imperfections was doubtless the haste with which the field work for these earlier maps was done, as the result of pressure for square miles rather than for accuracy of results; another reason may have been the habit acquired in non-glaciated mountains, of drawing spurs and valleys with normal forms instead of with the specialized features of glacial forms. Still a third reason must have been the want of sufficient inspection in the field, in the absence of which many errors clearly visible on the scale of publication were given the authority that their appearance on official maps naturally carries. A map drawn with some appreciation of the differences between normal and glacial forms would, I believe, be significantly unlike the Leadville sheet.

The Colorado Midland railroad tunnels through the northern part of the Sawatch range under Hagerman pass, next north of Mt. Massive. The ascent to the tunnel, after one crosses the Arkansas river west of Leadville, is full of scenic interest, more especially when the scenery is interpreted in view of its glacial origin. The ride must have been more remarkable a few years ago than now; for the railroad originally had a shorter tunnel at a height of about 11,800 feet; now it has a longer tunnel, about two miles in length, at an altitude of 11,000 feet; thus saving a heavy climb for the trains and two hours, we were told, of time, but depriving the traveller of the sight of the upper cirques that was formerly offered. Yet even the present route is an unusual one. It turns west from the Arkansas valley and enters a morainic amphitheater through a stream-cut notch; it then ascends the spur-less, ravine-less southern side of the glacial trough to the trough-head, in the neighborhood of which the tunnel begins. During the ascent, one sees to great advantage the trough floor, of which the lower part is occupied by an artificial reservoir, and the middle part by a green meadow through which a stream wanders in a somewhat braided course. For a while the road follows the inner slope of the southern lateral moraine; then the southern rock wall of the trough. The trough forks near its mid-length; two branch glaciers that here joined must have been of about equal size, as neither branch trough hangs over the floor of the other. The simplicity of the form of the trough wall is evidently an advantage in the laying of the railroad; for the wall offers neither spurs to turn around nor side ravines to bridge across. In

this feature the location of the road recalls that of the Canadian Pacific in its ascent to Rogers pass; in that case there are to be sure some formidable ravines to bridge over, yet their depth is small compared to that of the great trough valley into which the streams plunge down, and along whose side the railroad ascends to the pass.

After running through the tunnel the train comes out upon the broad floor of a high-level valley, which descends westward. After a short distance the floor of the valley suddenly drops at "Hellgate," and a deep rock-walled trough opens abruptly far below the track. This seems to be an example of what the Swiss glacialists now call the "trough head," above which the cirque floor broadens out to the cliffs that rise to the sharpened ridges and peaks. Continuing westward the road descends along the north wall of the deep trough and soon comes to a remarkably well-formed lateral moraine, by which some small meadows are enclosed against the apparently unglaciated mountain slope, high above the bottom of the trough. Hereabouts a larger valley, seemingly the main trough of this glacial system, comes from the southeast and receives in somewhat hanging fashion the trough we have been following. A little farther on the railroad loops back eastward around a sharp curve on the north side of the main trough. A mile or more eastward on the loop the road enters what I took to be the lower part of the branch trough below Hellgate, there to loop again and descend westward into the larger main trough. Soon a remarkably well-defined hanging valley is seen coming in from the southeast on the southern side of the main trough; two sharp moraines lie around its mouth, one within the other, on the walls of the main trough; the stream that falls from the hanging valley is cutting a narrow ravine in the main trough wall. The floor of the main trough is broadly opened here; a few miles farther down the valley, westward, it is distinctly narrower; but nightfall here came on and made it impossible to determine the details of this change of form.

It is recognized that notes such as are given in the preceding paragraphs, based on hurried records made in a passing train, cannot have great value; but inasmuch as they give more information about the well-developed glacial features on Mts. Elbert and Massive than can be found elsewhere, they are allowed a place here, partly in the hope that they may lead to the selection of the Hegerman pass district for careful study by some specialist in the study of mountain sculpture by normal and by glacial agencies.

EXPLANATION OF PLATE.

A. La Plata peak and the hanging valley of Crystal lake gulch, Sawatch range, Colorado.

B. Truncated spurs on the south side of Lake creek trough, between La Plata peak and Mt. Elbert, Sawatch range.

A. LA PLATA PEAK.

B. TRUNCATED SPURS LAKE CREEK TROUGH.

The following Publications of the Museum of Comparative Zoölogy are in preparation: —

Reports on the Results of Dredging Operations in 1877, 1878, 1879, and 1880, in charge of ALEXANDER AGASSIZ, by the U. S. Coast Survey Steamer "Blake," as follows: —

H. AUGENER. The Annelids of the "Blake."
C. HARTLAUB. The Comatulae of the "Blake," with 15 Plates.
H. LUDWIG. The Genus Pentacrinus.
A. MILNE EDWARDS and E. L. BOUVIER. The Crustacea of the "Blake."
A. E. VERRILL. The Alcyonaria of the "Blake."

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of ALEXANDER AGASSIZ, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

LOUIS CABOT. Immature State of the Odonata, Part IV.
E. L. MARK. Studies on Lepidosteus, continued.
" On Arachnactis.
R. T. HILL. On the Geology of the Windward Islands.
W. McM. WOODWORTH. On the Bololo or Palolo of Fiji and Samoa.
AGASSIZ and WHITMAN. Pelagic Fishes. Part II., with 14 Plates.

Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieutenant Commander Z. L. TANNER, U. S. N., Commanding, in charge of ALEXANDER AGASSIZ, as follows: —

A. AGASSIZ. The Pelagic Fauna.
" The Panamic Deep-Sea Fauna.
H. B. BIGELOW. The Siphonophores.
K. BRANDT. The Sagittae.
" The Thalassicolae.
W. R. COE. The Nemerteans.
W. H. DALL. The Mollusks.
REINHARD DOHRN. The Eyes of Deep-Sea Crustacea.
H. J. HANSEN. The Cirripeds.
HAROLD HEATH. Solenogaster.
W. A. HERDMAN. The Ascidians.
S. J. HICKSON. The Antipathids.
J. P. McMURRICH. The Actinarians.
E. L. MARK. Branchiocerianthus.
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THEO. STUDER. The Alcyonarians.
M. P. A. TRAUSTEDT. The Salpidae and Doliolidae.
H. B. WARD. The Sipunculids.
W. McM. WOODWORTH. The Annelids.

PUBLICATIONS

OF THE

MUSEUM OF COMPARATIVE ZOÖLOGY

AT HARVARD COLLEGE.

There have been published of the BULLETIN Vols. I. to XLII., and also Vols. XLIV., XLV., and XLVII.; of the MEMOIRS, Vols. I. to XXIV., and also Vols. XXVIII., XXIX., XXXI., and XXXII.

Vols. XLIII., XLVI., XLVIII., XLIX., and L., of the BULLETIN, and Vols. XXV., XXVI., XXVII., XXX., XXXIII., XXXIV., and XXXV., of the MEMOIRS, are now in course of publication.

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The following publications are in preparation:—

Reports on the Results of Dredging Operations from 1877 to 1880, in charge of Alexander Agassiz, by the U. S. Coast Survey Steamer "Blake," Lieut. Commander C. D. Sigsbee, U.S.N., and Commander J. R. Bartlett, U.S.N., Commanding.

Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieut. Commander Z. L. Tanner, U. S. N., Commanding, in charge of Alexander Agassiz.

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Contributions from the Zoölogical Laboratory, Professor E. L. Mark, Director.

Contributions from the Geological Laboratory, in charge of Professor N. S. Shaler.

These publications are issued in numbers at irregular intervals; one volume of the Bulletin (8vo) and half a volume of the Memoirs (4to) usually appear annually. Each number of the Bulletin and of the Memoirs is sold separately. A price list of the publications of the Museum will be sent on application to the Librarian of the Museum of Comparative Zoölogy, Cambridge, Mass.

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AT HARVARD COLLEGE

Vol. XLIX.

GEOLOGICAL SERIES, Vol. VIII, No. 2.

THE WASATCH, CANYON, AND HOUSE RANGES, UTAH.

By W. M. Davis.

With Three Plates.

CAMBRIDGE, MASS., U. S. A.:

PRINTED FOR THE MUSEUM.

December, 1905.

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F. E. BEDDARD. The Earthworms.
H. B. BIGELOW. The Medusae.
R. P. BIGELOW. The Stomatopods.
S. F. CLARKE. The Hydroids.
W. R. COE. The Nemerteans.
L. J. COLE. The Pycnogonida.
W. H. DALL. The Mollusks.
C. R. EASTMAN. The Sharks' Teeth.
B. W. EVERMANN. The Fishes.
W. G. FARLOW. The Algae.
S. GARMAN. The Reptiles.
H. J. HANSEN. The Cirripeds.
H. J. HANSEN. The Schizopods.
S. HENSHAW. The Insects.
W. E. HOYLE. The Cephalopods.
C. A. KOFOID. III.[3] The Protozoa.
P. KRÜMBACH. The Sagittae.
R. VON LENDENFELD. The Sponges.
H. LUDWIG. The Holothurians.
H. LUDWIG. The Starfishes.
H. LUDWIG. The Ophiurans.
J. P. McMURRICH. The Actinaria.
G. W. MÜLLER. The Ostracods.
JOHN MURRAY. The Bottom Specimens.
MARY J. RATHBUN. The Crustacea.
HARRIET RICHARDSON. II.[2] The Isopods.
W. E. RITTER. The Tunicates.
ALICE ROBERTSON. The Bryozoa.
B. L. ROBINSON. The Plants.
G. O. SARS. The Copepods.
H. R. SIMROTH. The Pteropods and Heteropods.
TH. STUDER. The Alcyonaria.
T. W. VAUGHAN. The Corals.
R. WOLTERECK. The Amphipods.
W. McM. WOODWORTH. The Annelids.

[1] Bull. M. C. Z., Vol. XLVI., No. 4, April, 1905, 22 pp.
[2] Bull. M. C. Z., Vol. XLVI., No. 6, July, 1905, 4 pp., 1 pl.
[3] Bull. M. C. Z., Vol. XLVI., No. 9, September, 1905, 5 pp., 1 pl.

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THE WASATCH, CANYON, AND HOUSE RANGES, UTAH.

By W. M. Davis.

With Three Plates.

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No. 2.—*The Wasatch, Canyon, and House Ranges, Utah.*

BY W. M. DAVIS.

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INTRODUCTORY NOTE.

The following notes on the Wasatch, Canyon, and House ranges in Utah are the results of a short excursion in the summer of 1904, and are to be taken as a continuation of a paper on The Mountain Ranges of the Great Basin in volume 42, number 3 of this Bulletin. My party included Prof. E. S. Hinckley of Provo, Utah, who had rendered much practical assistance in getting horses and outfit ready before the arrival of the rest of us from the east; Prof. L. G. Westgate, of Ohio Wesleyan University, Delaware, Ohio; Mr. G. C. Curtis, of Boston; and M. Meurice Allorge of Paris. We were in the field from July 12 to July 27.

THE WASATCH RANGE.

The Spanish Peak Wasatch. The part of the Wasatch range between the through-going cross valleys of Spanish fork and Hobble creek, to which special attention was given in my previous paper, was visited again, partly that it should be seen as a type form by the other members of the party, and also with the object of determining how far its eastern or back slope might retain remnants of pre-faulting form.

Plate 1 A shows a part of the mountain front, where the triangular end of a large spur between two large valleys is divided by three small ravines into four small spurs with more or less distinct terminal facets. The small ravines open on the Bonneville beach; recent fault scarps interrupt the slope of the Bonneville shore deposits, but do not exhibit the forward-reaching rock platforms that should be visible if the spur-end facets had been cut by the Bonneville waves, without aid by faulting. The foreground plain is the surface of a large delta at the Provo level. The view along the mountain base given in my previous paper was taken from the apex of the highest of the facets here shown.

It may be well to state that special attention is given to details of form, such as are here illustrated, and that relatively little attention is given to structure apart from its relation to form, because it is essentially upon morphological evidence that decision must be made as to the origin of the range by faulting or otherwise. If the range were described only with respect to the age of its strata, the attitude in which they stand, the internal folding and faulting that they have suffered, and if no details were given as to the relation of base line and mountain front to structure and sculpture, it would not be possible for a reader to judge for himself whether block-faulting has played any part in the origin of the range or not. In the solution of any problem of this kind, there is a certain group of features whose critical determination is essential, and there are various other groups of features whose determination is more or less irrelevant. The selection of the various features that are essential to the solution of the problem under discussion cannot, I believe, be accomplished without a careful deductive consideration of the problem as a whole; and it is for that reason that the deductive side of the problem was presented in some detail in my previous paper. Following the results then reached, I shall now again give special attention to matters of mountain form, especially to the details of form along the mountain base line, and to the relation of these details to the structures of the mass there exhibited; while various matters that would receive close attention in a conventional geological description of the range are here passed over rapidly; not because they are altogether irrelevant, but because in the short time at the disposal of our party it seemed best to attend to matters that bore most directly upon the problem of block-faulting.

On July 13 we went up one of the deeper valleys on the western face and reached a rounded knob on the eastern side of the range at an altitude of about 8,400 feet: the summits of the range lay a mile or two to

the west and rose 500 or 1,000 feet above us. All the eastern slope was well dissected by sharply cut valleys of no manifest arrangement; the hills and spurs between them rose in graded slopes to rounded summits, as in figure 1. The structure of the mountain mass had no distinct influence on its form; the rocks were mostly gritty quartzitic beds, with some limestones and shales; the prevailing dip was eastward with moderate angles at first, and steeper farther eastward from the crest; but outcrops were rarely seen, even in the ravines that we followed. Six small and imperfectly developed cirques were noted along the east side of the range crest, as shown in the accompanying figure; their floors were not far from 8,500 feet in altitude. To the eastward

Fig. 1.— The crest and higher eastern spurs of the Spanish peak Wasatch: looking west.

of our point of view, a maturely dissected highland continued to the horizon; it was a part of the Plateau province, of which Sevier plateau, far to the southeast, was the most distinct element. It thus appears that nothing was seen on the back of this part of the Wasatch that could be interpreted as belonging to an earlier cycle of erosion; hence the features of the back slope confirm the evidence of mature post-faulting sculpture that is gained from the range front, where no sign of the initial fault face of the uplifted block is now to be distinguished, except in the little terminal facets which truncate the spurs along the simple base line by which the range is here so decisively bounded on the west.

In my previous paper, the wide-open cross valleys cut by Spanish

fork and Hobble creek at the two ends of the Spanish peak mass were mentioned (p. 146) as more maturely opened than certain other valleys of the Wasatch, farther north. A closer examination of the side slopes of these cross valleys showed them, however, to be in no essential respect unlike the side slopes of the ravines that have been carved in the west face of the mountain mass between them, although the cross valleys are more conspicuous because they are cut down so deep and are continuous through the range. The valleys here are wider open and their slopes are better graded than is the case with the canyons of the Provo Wasatch, next farther north, because the limestones there are more resistant to arid weathering than are the arenaceous beds of the Spanish peak mass. We had good opportunity to note these features during the morning ascent and again in the afternoon descent when we returned to the western base of the mountain by way of the canyon of Spanish fork. It is worth mentioning that the spurs which descend into the cross valleys have terminal facets, like those which terminate the spurs at the western base of the range. This is evidently because the cutting action of the streams in the cross valleys replaces the cutting action of the fault on the range front.

While making the descent we had a good sight of the high-level Bonneville terraces in Diamond creek valley, a northern branch of Spanish fork several miles back in the mountains. The terraces were distinctly of stream origin, as there was a strong down-valley slope on their upper surface which originally led down to the Bonneville level at the delta margin. We were thus better prepared than before to appreciate Gilbert's explanation of the smaller size of the ancient deltas at the high Bonneville level than at the lower Provo level: for during the stand of the ancient lake at the Bonneville level all the deeper valleys that were flooded far back into the mountains had to be aggraded, and so much material was needed for this purpose that the surplus for forward delta growth in the main body of the lake was small; but when the lake fell to the Provo level, the waste accumulated in the valleys was easily and promptly devoted to delta building in the lake itself; and hence the Provo deltas rapidly grew to large size.

Our camp for the night of July 13 was at an isolated ranch about two miles northwest of the mouth of Spanish fork canyon, and was notable for the strength of the mountain breeze that began early in the evening and blew with increasing strength all night and after sunrise the next morning. Everything movable was drifted away, and two of the party had a quarter-of-a-mile search down the wind for their hats.

The ranchman told us that the canyon wind was a regular occurrence, and others said that it was on account of this wind that the district close about the mouth of the canyon was unoccupied.

The Wasatch Front from Spanish Fork Canyon to Santaquin. The Spanish peak mass of the Wasatch stands to the east of the general line of the mountain front. The recession on the north is caused by an incurving of the base line at the southern end of the Provo mass, where the limestones that make the front and crest of that part of the range are all cut off in very suggestive fashion: the recession on the south is accompanied by the development of several well defined facets on the spurs that descend to the Bonneville delta of Spanish fork; these facets are conspicuous in the view from the line of the Rio Grande railroad, which passes near them on its way into Spanish fork canyon. The facets are especially large at the corner where the front of the range turns southward again, east of the village of Salem, and are shown at the left in figure 2. The question here arises again,

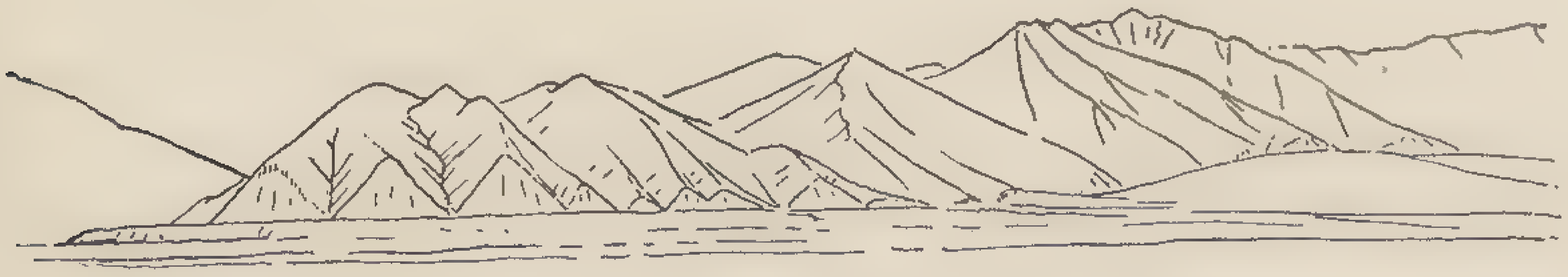

Fig. 2.— The Wasatch range, between the canyons of Spanish fork on the left and of Payson creek on the right; looking southeast.

whether the large facets of this kind are due to erosion by Bonneville waves, or whether they are normal fault facets, more or less battered by weathering to a graded slope. It is true that the facets at the corner of the range are well situated for effective attack by the lake waves; yet there does not seem to be a broad, forward-reaching rock platform beneath the facets, such as should certainly be found if tapering spurs of pre-Bonneville erosion in a non-faulted mountain mass had been cut back by wave action.

As the mountain front turns southwestward the facets become smaller, but they are easily recognized at the ends of many spurs along the mountain base for 8 miles to Payson canyon. In the latter half of this distance the base line of the mountain rises several hundred feet over the highest Bonneville shore line; yet even there recent fault scarps are seen in the outwashed piedmont gravels; hence the recent slips and scarps elsewhere seen in the Bonneville deltas at the Wasatch base line should not be ascribed only to the settlement of the delta

sands and gravels, as has been suggested, but rather to the recent displacements of the mountain mass, as Gilbert has explained them.

Not far northeast of Payson canyon there are low rock-like mounds in the piedmont slope, as if here a part of the down-faulted mountain mass were still to be seen; but they lay too far aside from our road to be examined.

Between Payson and Santaquin, in the neighborhood of the village of Pondtown, the mountain base is below Bonneville level, and here several rather well defined spur terminals have the Bonneville shore line slightly marked across the middle of their triangular facets, as in figure 3. In such a case it is evident enough that the facets cannot be the work of lake waves; and thus such an origin is made unlikely in other places as well.

FIG. 3.— A facetted spur crossed by the Bonneville shore line, near Pondtown.

Between Pondtown and Santaquin, the gently convex base line of the range is clearly discordant with the mountain structure. About the middle of the base line a series of lighter colored strata dip into the mountain below the darker strata that form the higher slope; but towards either end of the base line the darker strata gradually descend to the base line, and the lighter colored strata disappear underground. Such discordance of form and structure, coupled with the simple curvature of the base line, the sharp cut ravines on the mountain face and the somewhat facetted spur-ends between them, must be taken as strong witnesses for the fault-block origin of the range. Next south of Santaquin, there are several outlying rock masses, west of the general mountain front, but their relation to the mountain was not clearly made out.

The Wasatch Front from Santaquin to Nephi. This southward stretch of 20 miles gave the most unequivocal evidence of block faulting and elaborate carving, particularly well displayed near the little village of Mona. To the north, as far as Spanish fork, the attitude of the strata is as a rule not particularly well exhibited, presumably because there are no contrasts of hardness or color of sufficient strength, whereby the relation of structure and form should be brought out: but south of Santaquin the resistance of successive members of the stratified series in the mountain face becomes more varied, and structure is displayed in form with satisfactory clearness. The strike of the strata is seen to be northeast-southwest, with strong and variable dips to the southeast. As a result, the ridges and valleys that

are determined by the stronger and weaker strata run oblique to the well maintained north-south trend of the range as a whole. This relation is roughly shown in figure 4, sketched near Mona, looking eastward. The lowest members of the series, A, A, form the base of the range on the left (north); these were taken to be the same beds that are mentioned above as appearing locally at the base of the range along the slightly convex base line between Spring Lake and Santaquin. Next comes a strong ridge, B, B, somewhat dissected by obsequent ravines on its outcrop face, and ending in small, slightly facetted spurs along the base line: this was taken to be made of the same series of darker strata which rose to the crest of the range next north of Santaquin. It is most significant to note the manner in which this ridge is obliquely cut off where it descends to the base line, so that it ends accordantly with the weaker strata that lie, strati-

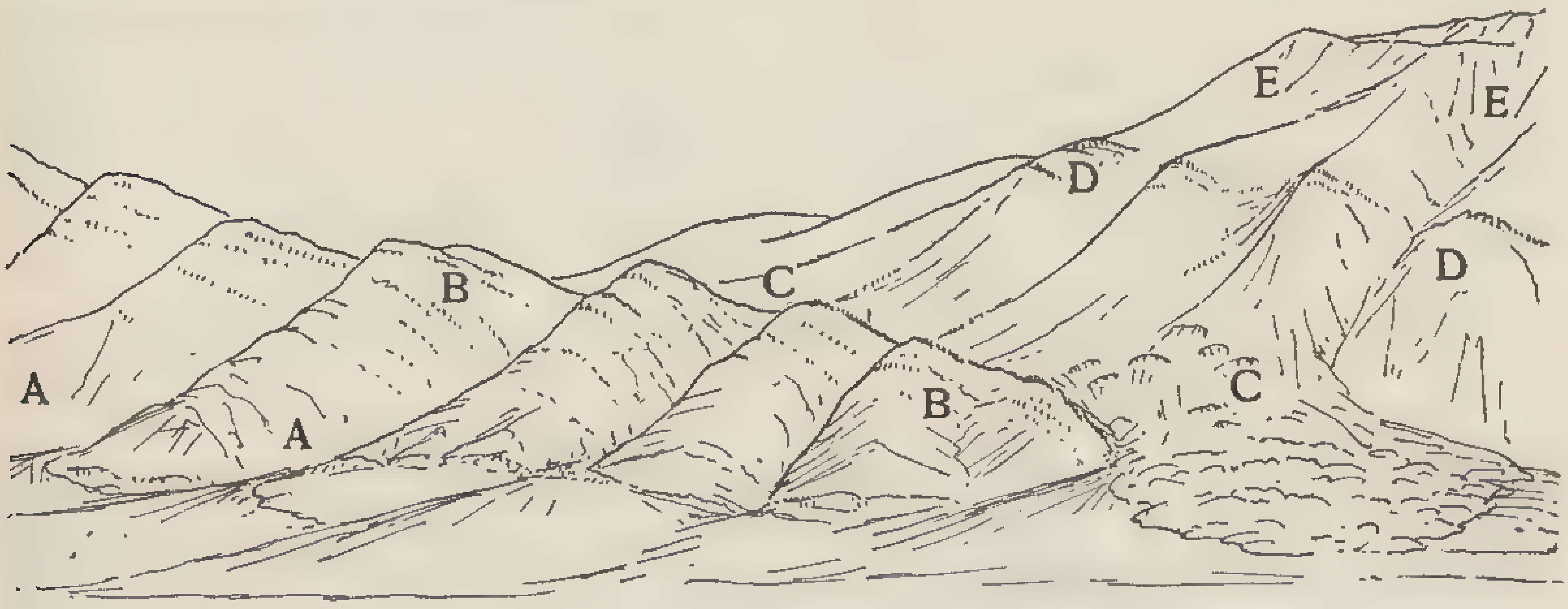

Fig. 4.— The oblique monocline of the Wasatch range, looking east from Mona: Mt. Nebo on the right; a landslide on the base line below.

graphically, below and above it; instead of projecting farther forward into the plain, as it certainly should do if the mountain were not a fault block, moderately consumed by post-faulting erosion, but were the residual of a once much greater mass that had been worn back without any aid from faulting. Back of the oblique ridge is an oblique subsequent valley eroded along the strike of a belt of weaker strata, C, C, which thus determines location of a rather low pass in the range. The most curious feature about these weak strata is the small landslide of recent date, in which their incoherent materials have sprawled forth on the piedmont slope; it is the only case of the kind that has come under my observation on the Wasatch front, and it indicates that an uplift of the mountain block has here occurred so recently and so suddenly as still to be marked by the

spilling of a considerable body of the weaker strata hundreds of feet forward from the mountain base. Overlying the weak strata are two groups of stronger beds, D, D, and F, F, separated by a

FIG. 5.— Mt. Nebo, at the south of the oblique monocline of the Wasatch: landslide at right base.

somewhat weaker group; and as a result the range here regains its height in the fine summits of Mt. Nebo. The upper strata were regarded by Professor Hinckley as corresponding to the Carboniferous series that he knows well in the Provo mass. A view of this part of the range, looking southeast from a point a few miles north of Mona

FIG. 6.— Diagram of facetted spurs and recent fault scarp, Mt. Nebo Wasatch.

is given in figure 5; the oblique subsequent valley is here less clearly visible than from points farther south. Three small cirques are seen on Mt. Nebo, the northernmost being poorly defined. A small glacier is said to occupy a cirque on the eastern side of the mountain.

Recent faulting along the mountain base is exceptionally well shown hereabouts. The gray scarp of the fault line is fresh and continuous across spur bases and valley mouths, as in figure 6. An excellent example of repeated faulting is seen in a fan about three miles northeast of Nephi, as in figure 7. The earlier fault here had a displacement of about 100 feet; then a valley several hundred feet wide was opened in the uplifted part of the fan; after this a smaller displacement of about 20 feet occurred, making a very light colored band along the base of the earlier scarp and continuing for a mile or more southward through the piedmont waste slope. Like the recent faults north of Payson canyon, these are above the Bonneville shore line.

It is certainly significant that none of the recent faults have been observed within the mountain mass, although if they occurred on the front slope of the Wasatch in this district they could hardly have escaped detection. Even on the lines of the older transverse faults

FIG. 7.— Double fault scarp, base of Mt. Nebo Wasatch.

which traverse some of the Basin ranges, no recent movements have been reported; but on the contrary these interior transverse faults have, in nearly all reported cases, been followed by a great amount of erosion, sufficient in some examples to bring about the topographic reversal of the faulting, and make the surface of the heaved block lower than that of the thrown block. It is therefore legitimate to regard the transverse faults, along with the composition, the folds, and the fossils that occur within the mass of a range, as relatively remote contingencies; they are not necessarily connected with the problem in hand, excepting in so far as they, as well as the composition, fossil contents, and folds of the mountain rocks, are disregarded by the base line which cuts across them all indifferently and thus shows their antiquity in contrast to its recency.

There was an element of personal satisfaction that resulted from this part of the excursion along the Wasatch front. The details of mountain form here observed and sketched in their actual occurrence gave good warrant for the correctness of a hypothetical diagram, here reproduced in figure 8, which I published in *Science* for September

20, 1901, when reviewing Spurr's paper on the Origin and Structure of the Basin Ranges. The diagram was not intended to be a picture of any actual range, for at that time I had not gained any personal acquaintance with the Basin ranges. It was simply designed to show an imaginary block of various structures, that had been faulted, uplifted and submaturely carved; it was a graphic summary of the consequences reasonably deducible from the theory of the block-faulting of the Basin ranges. When the essential features of such a diagram are found in nature, one may fairly conclude that the consequences of the theory, summarized in the diagram, are correctly deduced,

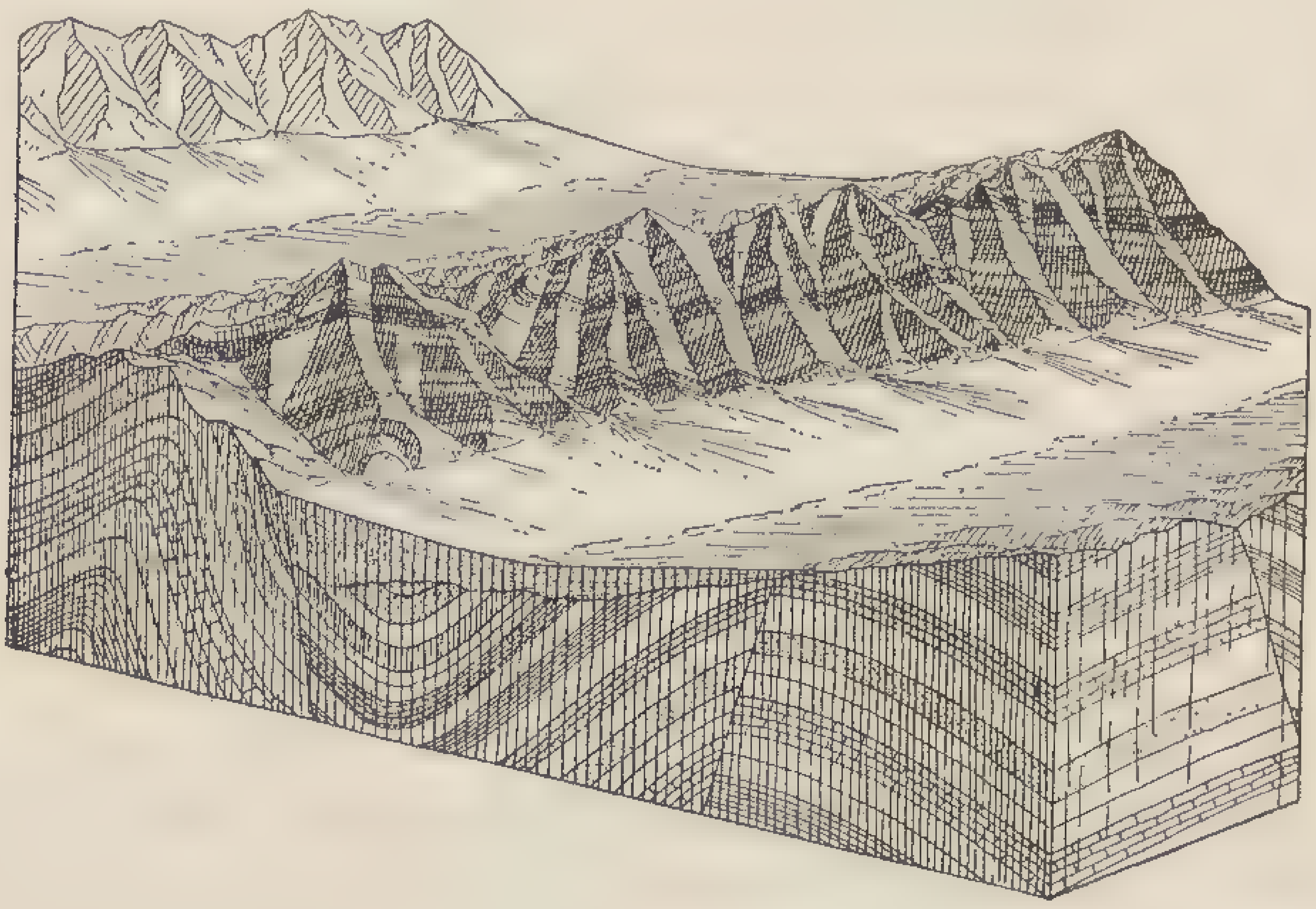

Fig. 8.— Diagram of a mountain carved on a faulted block of previously deformed and denuded strata; reprinted from Science, Sept. 20, 1901.

and that the theory from which such consequences are deducible furnishes the true explanation for the observed facts which correspond to the inferred consequences.

We spent the night of July 14 at Nephi. Here the Wasatch range proper may be said to end, for the deep and wide valley of Salt creek comes after the Mt. Nebo mass. The valley comes in from the northeast, apparently the result of easy erosion on the next following Permian clays, which are everywhere very weak in the Plateau province. Beyond the oblique valley is an oblique ridge, trending northeast-southwest, like those already described; and rising behind it (southeast) was a still higher oblique ridge or escarpment with bold red cliffs, presumably of the Trias. The Wasatch fault therefore probably continues southward, but our turn westward the next day gave us no further sight of it.

The open valley or basin that we followed southward from Santaquin to Nephi was bounded on the west by a low range of subdued form, whose eastward slope had many sprawling spurs that gradually melted away in the piedmont plain. Isolated hills sometimes rose from the plain farther forward than the spur ends. The piedmont wash headed in open valleys of gentle grade, interlocking with the low sprawling spurs. Spurs and valleys blended together almost too delicately to be shown properly in an outline sketch, but their relation may perhaps be suggested in figure 9, drawn from parts of the range west of Nephi.

FIG. 9.— Diagram of graded spurs in a subdued range, west of Nephi.

The recognition of these gentle features in the well dissected and subdued ranges, in contrast to the stronger and sharper elements of form in the higher ranges, is an important element in the discussion of the ranges of the Great basin.

Different Types of Mountain Fronts. The peculiar features of the Wasatch front, as here described, may perhaps be better appreciated in their relation to the theory of fault-block mountains in general, if two examples of the forms of vigorous mountain fronts of other origin are adduced.

A simple type of vigorous mountain front, in which structure and form are closely accordant, is found along the Rocky mountain border west of Denver. Here a broad uplift has brought the crystalline mountain core above the level of the horizontal strata of the Plains, the two being separated by a strong monoclinal flexure of the Palaeozoic and later strata, such as was long ago well shown in Holmes's illustrations of Hayden's early reports; for example in Section III, p. 31, of the Report for 1873. The mountain border does not, however, retain in any close way the form initially produced by deformation. Extensive erosion has worked upon the uplifted mass; the weaker strata of the Plains have been worn down to moderate relief, even to a peneplain over large areas, and the mountains now rise only where the uplifted masses are composed of resistant rocks. The most impor-

tant peculiarity of this type of mountain front in the present connection is that it has been determined essentially by a single deformation, upon which erosion has worked simply to carve the deformed mass, thus leaving its more resistant parts in prominent relief and causing the base line to follow the boundary between the strong and the weak structures. Such an example may therefore be taken as the type of a monogenetic mountain front. It is quite possible that more than one cycle of erosion is here concerned, but the uplift by which the present cycle was introduced seems to have been so widespread and uniform that it did not significantly affect the structural features of the range. The high-standing crystalline mass of the Front range is generally sharply dissected, yet in certain districts its uplands retain an accordant altitude which strongly suggests the work of an earlier cycle than that now current. This has been pointed out for the Front range north of Pikes peak by Emmons. The upland is well seen northeast of South park from the line of the Colorado Midland railroad; somewhat farther south, Pikes peak has every appearance of being a huge monadnock, rising above the upland level. The valleys that have been eroded in the upland are narrow as a rule, and remain narrow until they pass the foot-hill ridge or hog-back of upturned Mesozoic strata; then the country opens so broadly that the valley is almost forgotten, and it is not at first easy to recognize the great erosion that the Plains have suffered. One of the best points to correct the false impression that the Plains are but slightly modified from their original surface is near Trinidad, Colorado, where Raton mesa, a mass of weak Plains strata capped with a heavy lava sheet, surmounts by some thousand feet the denuded, nearly peneplained surface to the north. Certain parts of the Himalayas in northern India offer examples of this type of mountain front, but probably less modified by erosion than in the case of the Colorado Front range, as may be seen on the road that ascends from the plain of the Punjab to Simla.

A very different type of mountain border is found in polygenetic ranges. The type of this class may be taken from among those ranges which enclose the intermont basins of Montana, as illustrated, for example, in the Three Forks folio, U. S. Geological Survey. Here the mountains are the result of at least two periods of deformation, and the second deformation or warping was discordant with the first; that is, instead of merely intensifying the folds or faults of the earlier period, the later deformations introduced a new system of warpings. As a result the belts of the earlier deformed

and denuded structures, which are now warped upward in one direction to a mountain crest, are warped downward in the other direction and descend beneath the floor of an aggraded basin. The base line of such ranges does not accord with structural lines; the quaternary deposits, that have been supplied to the depressions or basins by the erosion of the uplifted areas, lap unconformably on the mountain slopes and irregularly cross whatever structures have there been bent down. This kind of discordance between structural features and mountain base is repeated on a larger scale along the western border of the Sierra Nevada, where the Quaternary deposits of the Valley of California lap over the down-warped surface of the denuded mountain mass; and again on the southern side of the Alps, where the Quaternary deposits of the Plain of Lombardy overlap various denuded belts of the mountain-making rocks. A border line of this kind might be expected on the back slope of a tilted Basin-range block. The simplicity of the border would depend in large measure on the faintness of relief of the block surface before faulting took place.

The front border of a fault block range would resemble the first of the two previous types in respect to its relatively simple base line, but would differ from it in presenting no essential relation between base line and structure; it would resemble the second type in possessing a base line that ran indifferent to the structure of the mountain mass, but would differ from it in the greater abruptness with which the mountain front would rise over the piedmont plain.

It thus appears that various types of mountain border and base line are appropriate each to its own origin and history. Hence on returning to the Wasatch mountains with these various examples in mind, one is all the more convinced that continued upfaulting and elaborate carving of a mountain block give the only adequate explanation for such a cleft anticline as is found in the Provo mass, with its simple base line and sharp cut canyons; for such a carved escarpment of nearly horizontal strata as is seen in the Spanish peak mass, with its gracefully curved base line, its facetted spurs, and its narrow-mouthed ravines; or for such an obliquely truncated monocline as is presented in the Mt. Nebo mass, with its obliquely carved ridges and valleys, its facetted spurs, its spilled weak strata, and its continuous recent fault along the mountain foot.

It should be remembered however that the Wasatch is not properly a member of the Basin range system. Whatever history the Wasatch range may have, we must not infer that the Basin ranges necessarily have the same history. But on the other hand the evi-

dent faulting of the Wasatch block makes this range a good training ground for whoever would go into the desert farther west and learn there, one range at a time, what manner of mountains are to be found in the Great basin.

The Canyon Range.

From Nephi to Lemington. We crossed the subdued range west of Nephi by a low notch on the morning of July 15, and descended into a broad intermont plain or basin, known as Dog valley, which we traversed to the southwest. Here we saw farther westward, but not very clearly on account of the increasing dustiness of the air, the confluence of the lowering northern end of the Canyon range with the subdued hills that stretch southward from the Tintic range. The drainage outlet of Dog valley was by a shallow but rather narrow ravine, cut through the rounded hills on the southwest, where the uplands were strewn with round-weathered boulders of trachyte. The ravine soon widened and led us southwestward into the eastern part of the so-called Sevier canyon in the Canyon range. This is hardly a canyon at all, but an open valley, with liberally dissected sides, although the rocks exposed in its enclosing ridges seemed to be of an enduring nature. They included some gray limestones, apparently very resistant to arid weathering, abundant red and purplish quartzites, and a very coarse conglomerate with some boulders up to five feet in diameter. The strike of all these beds was northeast-southwest; their dip was steep southeast or vertical. The openness of the so-called canyon and the abundant dissection of the ridges on its sides suggested that this range, if it ever were a faulted block, must have reached a much more mature stage of post-faulting dissection than is the case with the Wasatch. Terraces and silts of Lake Bonneville were seen on the sides of the canyon, and extensive deltas were found at its western end, all now dissected by Sevier river. As to the origin of the canyon, there is the manifest possibility that it is the work of the Sevier as an antecedent river, whose course was determined in the pre-faulting cycle and was persistently held across the uplifted fault block from which the existing range has been carved; but as to the correctness of this easy solution of the problem I shall not venture to express an opinion. The topography of the range, as indicated on the Sevier desert map sheet of the U. S. Geological Survey, is altogether inaccurate. The contours appear to have been

drawn from early surveys according to certain ill-defined general principles: they cannot be accepted as guides to actual forms.

A peculiar experience of this day's ride was the dust storm we encountered. The morning at Nephi was fresh and clear, the temperature at 6.30 being 70°. At 8.35, when we were crossing the notch in the subdued range west of Nephi, a light breeze from the southwest was blowing, and the sky was still clear. Before noon the breeze had increased to a warm gale, temperature 80° to 85°, bearing clouds of dust and making the sky chalky white, so that the sun cast only the palest shadows. Our ride directly into the dusty wind, which often carried grit and sand in its stronger flaws, was fatiguing and irritating. A curious accompaniment of the wind was a standing stratus cloud that formed somewhat northeast of the Canyon range and apparently high above it, increasing through the morning and fading away with the wind in the late afternoon and evening. Cloud filaments could be seen growing and knitting together as they entered the western or windward side of the cloud, and dissolving away as they floated out on the eastern or leeward side; yet the cloud as a whole stood motionless in the rushing air currents. There appeared to be no eddying or rolling of the cloud, such as is supposed to be associated with the Helm bar or cloud of northwest England. We stopped for the night at a Swede's ranch in Lemington, about two miles west of the outlet of Sevier canyon, where the river had opened a broad strath in the sands of the Provo delta. It was interesting to note that as the dusty gale decreased in the late afternoon, it veered to the west and northwest, and that it finally died away as a light breeze from the north after twilight was gone.

The Western Face of the Canyon Range. On July 16th we had a most interesting ride southward from Lemington along the western side of the Canyon range to Oak City, near its southwestern end. After rising from the Sevier strath to the delta level, there was a good view of the many ridges which make up the mountain mass. The northeast-southwest strike of the strata, observed in the canyon the day before, brings some of the ridges directly out to the western border of the range, where they end in rather gradual slopes. A little farther south, the strike turns southward, and continues for several miles nearly but not exactly parallel to the mountain border. At first the dip is rather steep into the axis of the range; farther on the beds are for a time nearly horizontal. The structure therefore presents discordant relations with the range border, and thus strongly suggests block faulting; but the valleys between the ridges are well opened and

have graded floors some distance inward from their mouths; the ridges are for the most part rounded off at their ends, and descend to the piedmont plain without the least indication of terminal facets; and no recent fault scarps were seen across the flat piedmont fans. Hence if the range is a faulted block, it is in a much more advanced stage of dissection than the Wasatch range, as has already been inferred from the openness of the Sevier canyon. Before pronouncing definitely on this point, more study of the base line is desirable. There is, however, yet to be described a curious feature which supports the supposition of block faulting.

About midway between Lemington and Oak City there is a huge, maturely dissected landslide at the western base of the range. We saw

Fig. 10.— Looking north along the western side of the Canyon range, from the in the middle distance.

it in the distance as we came up from the Sevier strath, when it seemed to be an outstretching spur, extending two or three miles from the body of the range; as such it was distinctly unlike the expectable features of a dissected block mountain. The road turns westward around the slide, and as we were told afterwards follows a Bonneville shore line that has been cut on its end, where many large boulders are exposed. We left the road and crossed over the slide near the range. It was composed of a most heterogeneous mixture of red and white quartzite, pebbly quartzite, and limestones, in fragments of all sizes up to six feet or more. Not a single ledge or outcrop was seen, although outcrops of quartzite strata, which dipped gently into the range, were abundant on the mountain flanks. Moreover the landslide was deeply and maturely dissected by branching valleys with graded side slopes; there was not a trace of the hill-and-hollow forms such as young landslides commonly possess. Many of the boulders had weathered and flaked to somewhat rounded forms. Hence the date

of the slide, like that of the inferred faulting of the mountain block, must be much less recent than that of the little slide and the modern faults along the base of the Nebo Wasatch. The size of the slide was surprising; it stretched continuously along the mountain base for at least two miles; its forward reach was estimated at two miles and a half; its height next to the mountain side must have been at least 500 feet, and probably more. The contact of the slide with the mountain side was rather well shown on the sides of a small valley which cut through both. The mountain face, there protected, seemed steeper than elsewhere. Several slides of similar character but of smaller size were seen farther south.

We spent the afternoon and night at Oak City, a small town that is

hills south of Oak City. A great landslide stretches westward from the range

irrigated by a stream from the neighboring range. Our camp was in a grassy orchard of apple and peach trees belonging to Mr. Fred Lyman. A sketch of the canyon range and the great landslide, figure 10, was made looking north from the hills south of the town about sunset: the slide extends in the distance from the middle of the right half of the figure to the first third of the left half. Part of the same view is shown in Plate 1, B. Our host made inquiries about the spur formed by the slide, saying that he had been much puzzled by it; he had looked into Leconte's "Elements of Geology," in hopes of there learning something about its origin, and had wondered if it could possibly be a great moraine, but had felt doubtful of such an origin because there was no mountain high enough above it to have fed a large glacier. He accepted our explanation that the spur is an old landslide, although against this explanation also there is the manifest objection that the mountain does not now seem high or steep enough to have provoked a fall. The evident answer to this objection is that the mountain may have been steeper and higher

than now when it was first upfaulted, and that it has lost its initial height and steepness in the same time and by the same processes that have sufficed for the dissection of the slide. On the other hand, if the Canyon range is regarded as a mere residual of a once far-and-wide stretching mountain mass, instead of as a maturely dissected fault block, the occurrence of such a landslide is altogether incompatible with the very advanced stage of erosion that must be as-

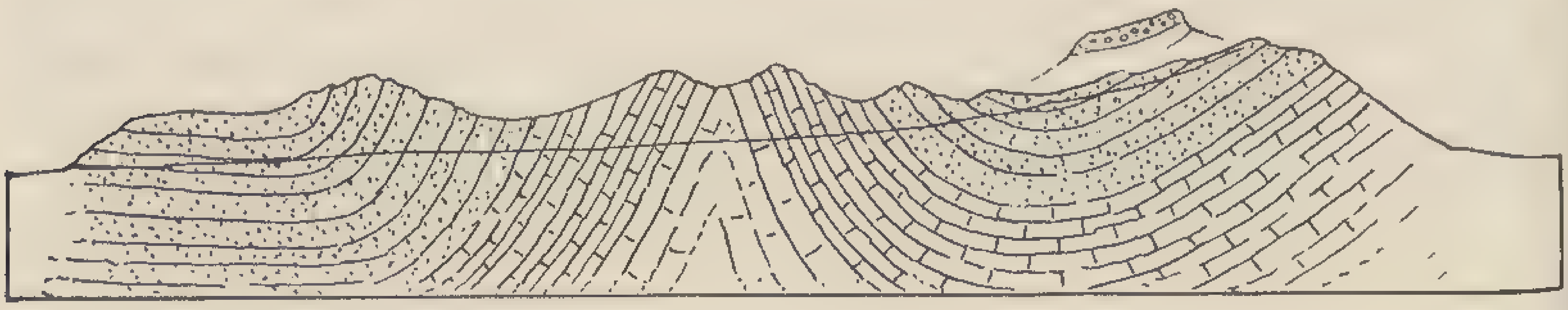

Fig. 11.— East-west section through the Canyon range along the valley of Oak creek: length about eight miles.

signed to the range when the slide occurred. The desert plain, at least 30 miles wide to the westward, might, as far as general geological possibilities are concerned, be the result of wide-spread peneplaination; but if that were the origin of the plain, the range at its border would have been reduced to slopes of so gentle a declivity that the occurrence of a large landslide on its decrepit flanks would be impossible.

Sections of the Canyon Range. The following day we made an

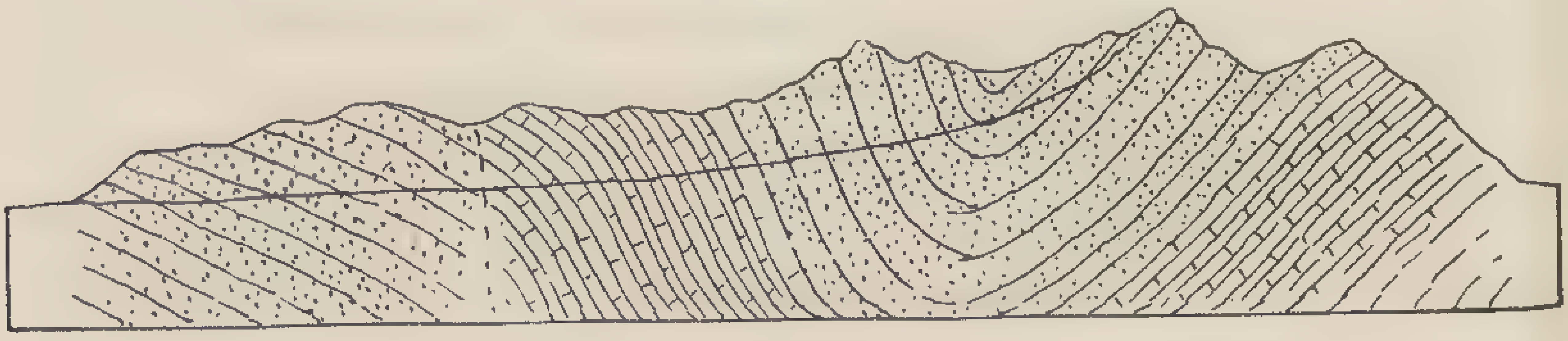

Fig. 12.— East-west section of the Canyon range along the valley of Dry creek, about two miles south of Oak creek: length, about eight miles.

excursion up the valley of Oak creek eastward to its head in the crest of the Canyon range, which here lies close to its eastern side. There we turned south along the slope of its eastern face, with the desert plain far below, and then returned to Oak City by the valley of Dry creek. The range is thoroughly dissected and its slopes are very generally graded. We saw no forms that could be safely referred to an

earlier cycle of erosion than the one now current. The eastern border of the range, as far as we could see it, seemed remarkably abrupt. Two east and west sections were rapidly sketched, as in figures 11 and 12, and are offered for correction by later observers. The strata certainly show abundant deformation and require great erosion in fashioning the present form of the range. Over a thousand feet of limestones and probably several thousand feet of quartzites were seen: they are believed to be of Carboniferous age. The western limb of the limestone anticline in the northern section along Oak creek seemed to be replaced by a fault in the section a few miles farther south along Dry creek. Figure 13 represents a more detailed view

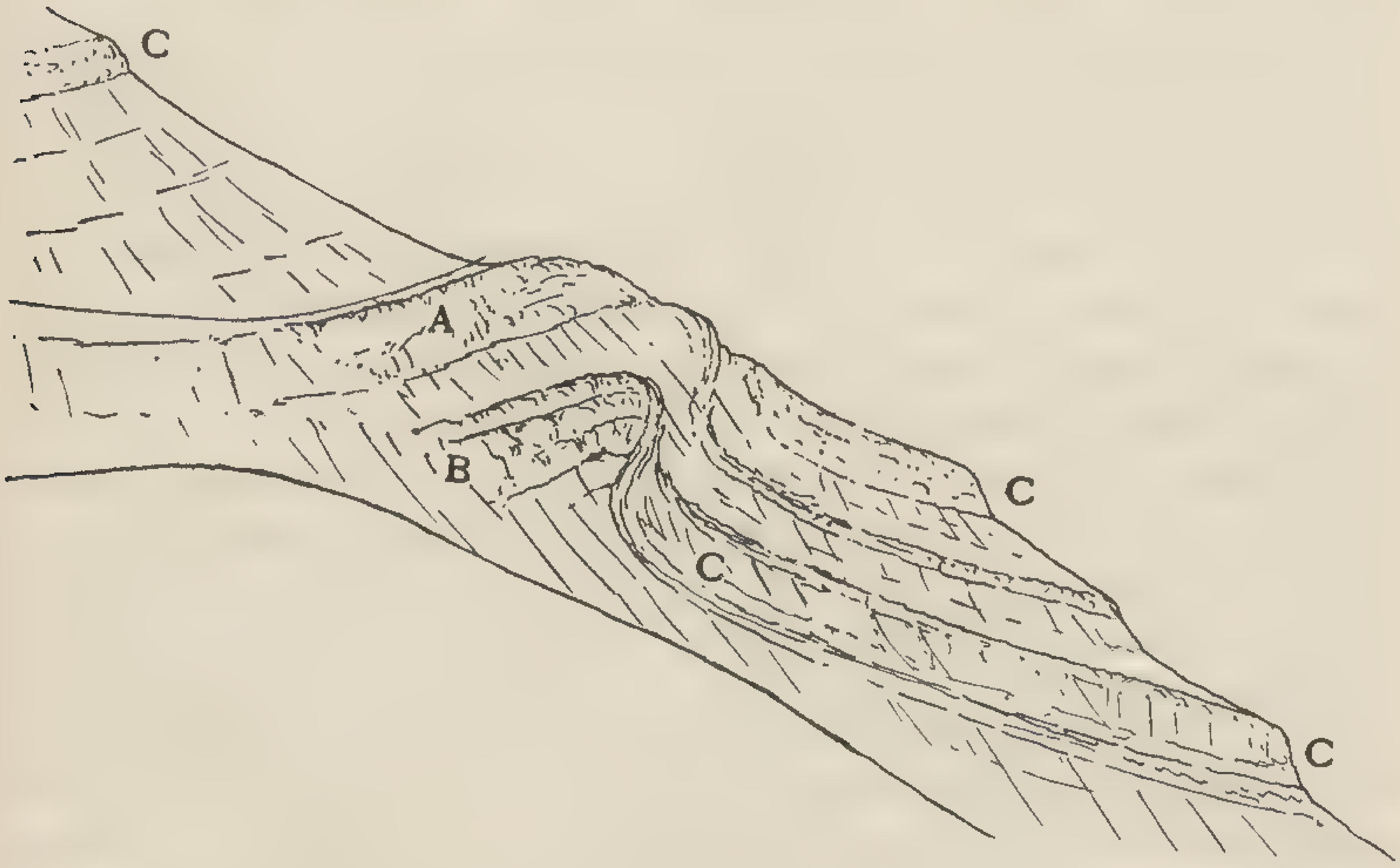

Fig. 13.— Detailed section on east slope of Canyon range, opposite the head of Oak creek; length of section about 1200 feet.

of a sharp shear or fault on the steep eastern slope of the range somewhat north of the col at the head of Oak creek. A mile or two farther south, no such deformation appeared; the eastern slope there was formed by outcrops of west-dipping limestones; hence it was inferred that the shear or fault in the northern section did not trend parallel to the eastern face of the mountain. If all the erosion indicated by these sections had taken place in a single cycle, it does not seem possible that the western border of the range could have its present relatively simple pattern. The range is therefore provisionally regarded as a fault block, perhaps faulted on both sides,

uplifted from a previously deformed and denuded region, and much dissected in the current cycle of erosion.

Like so many other isolated ranges in the Great basin the Canyon range offers a well limited subject for a geological thesis. Oak City and Lemington, the latter reached by rail, would be good centers for excursions. Oak City is a characteristic oasis, absolutely dependent on the little stream from the mountain, by which its fields are irrigated. Its limit of population is about reached.

The House Range.

The Sevier Desert. We crossed the Sevier desert westward from Oak City on July 18, stopping a few hours at Deseret on the Sevier river on our way to the House range. Several Bonneville shore lines were passed as we descended the gradual detrital slope southwest of the Canyon range. After riding some miles across the dreary expanse of the desert plain, we saw on the distant horizon first the trees and then in nearer view the haystacks and houses of Deseret. This oasis is watered from Sevier river, of which the channel is there 150 or 200 feet wide; the bed is 10 or 15 feet below the plain; at the time of our crossing there was only a shallow sluggish stream wandering in it. In recent years the water supply has proved insufficient for the fields; many of the trees by which the wide streets were once somewhat shaded have died, leaving the town with a desolate and saddened appearance, in contrast with the more thrifty condition of Oak City and various other towns through which we had passed. A reservoir is now in construction on the Sevier east of the Canyon range; the day we ascended that range, the site of the dam was seen, well determined by a notch cut by the river in a low ridge. As in all such cases, the relief gained by water storage will be at its best when the reservoir first comes into service; it will be 15 miles long, 1½ miles wide, 60 feet deep at the deepest, and will, it is estimated, supply 100,000 acre-feet of water. But the progressive filling of the basin by inwashed waste will cause its slow but continuous deterioration, for which even an increased height of the dam will provide only a temporary remedy. As a provisional expedient, the reservoir is of unquestionable value, but the importance of such devices is overestimated by those who look on them as the means of a permanent rescue from desert conditions. At the best, the area irrigable from reservoirs in this region can be but a very small fraction of the unmitigated desert, because

the rainfall even on the mountains is so pitifully small. It has been somewhat the fashion in recent years to say that the "great American desert" of the earlier explorers does not exist. This may be taken as a popular manner of correcting the previously wrong belief that a desert region is altogether uninhabitable. Truly it is marvelous to witness the transformation that irrigation has already produced in favored areas, and there is every reason to think that still greater transformations will be made when the great works of the Reclamation service are carried out. But it should not be forgotten that the total irrigable area can be only a very small part of the enormous arid region of the west, because the available water supply is so small. The great desert is a permanent feature in the arid western country, and its barrenness is only emphasized by the verdure of the oases that are dotted about upon it.

As our horses had no water in the ride of 22 miles from Oak City, we stopped at a house in the outskirts of Deseret where a small flowing well fills a shaded trough. The farmer had lived here for a score of years, depending chiefly on slightly brackish water pumped from a shallow well for house use; ten years ago he tried driving a deeper well, and after two days' work struck at a depth of 150 feet a sheet of excellent water which rose to the surface and has been flowing ever since. A railroad passes through Deseret: it originally ran to a mining district farther south; it is now in process of extension southwestward across the desert country with the aim of eventually reaching southern California. The effort to construct a road across so barren and desolate a region indicates how great is the value of a through line.

A Week about the House Range. The House range is so dry that there is only one ranch in its middle and southern part, where our trip extended. We therefore engaged a second wagon at Deseret to carry a week's supply of hay and grain for our horses, as well as some barrels to hold water for certain dry camps. A piece of rubber hose, with which to siphon water from barrel to bucket, was a useful item in the outfit. Thus reenforced we left Deseret in the late afternoon, followed the northern side of the Sevier flood plain, where occasional overflow in the spring and a certain amount of ground water supports enough grass to yield pasturage for scattered flocks, and made 12 miles westward to Craft's ranch, where a well of rather brackish water and some meadows from which hay is harvested, determine the dwelling place of a family. The next day, July 19, saw us across the western part of the desert, with a temperature of 98° in the early afternoon, and up the gentle slope of the eastern side of the House

range to Antelope Spring, where excellent water is to be had in small amount.

In so far as our observations concern the structure, form, and origin of the House range, they will be presented in systematic order, instead of in the order of dates; the following notes give our route and make mention of various items of interest during our week in this district. The localities mentioned may be identified on figure 17.

We spent July 20 near Antelope Spring, ascending to one of the great promontories of the steep western escarpment of the range, from which we could to advantage overlook the desert basin of Tule flat. A creamy playa occupied its central area, and its centripetal slopes were contoured with belts of varicolored desert vegetation. Many Bonneville shorelines were faintly marked on the sloping piedmont fans below us, 28 being counted with a field glass on one fan, and 33 on another. Some rain clouds formed over the range in the afternoon; they were characteristic for their small proportion of cumulus to cirro-stratus, and for the evaporation of their rain trails high in the air, even above the mountain ridges.

On July 21, we went on westward, descending by a good wagon road through a ravine in the mountain escarpment, then following down the stony piedmont slope and crossing the playa; here the temperature ranged from 98° to 100°, and while by no means agreeable it was not so uncomfortable as anticipatory descriptions had led us to expect. We found Indian Spring a little beyond the western border of the playa, with a good supply of somewhat warmish water. The highest Bonneville shore line that we crossed on the way was several hundred feet over the playa. At that level as well as lower down the piedmont slope, there were occasional small Bonneville deltas built on the great fans opposite the ravines in the mountain scarp, and many cut shore lines on the intermediate stretches; the cut shorelines have caused the erosion of many narrow gulches in the waste slope above them and the formation of corresponding small fans on the slope below them. It is noteworthy that the long piedmont slopes contain a much greater volume of stony waste than the Bonneville deltas, and are therefore of much greater antiquity than the Bonneville epoch. Indeed when the larger piedmont fans are viewed from a few miles away, the Bonneville shore lines make little impression on them. The shore lines and spits shown on the southern side of the fans at the base of the Sawtooth escarpment in figure 22 are drawn unduly large. A small ridge of dark limestone, isolated in the waste slope south of the road to Indian Spring, and of a

ragged wizened surface like much of the limestone in the arid country, was thinly mantled with a gray sintery incrustation, while white Bonneville silts were spread around its base.

The wash of angular stony scraps seems to be extending from the base of the piedmont slope and overspreading the finer central deposits of the intermont basin; the stones decrease in size as the distance from the mountain increases, but they are still angular. When they average only from one to three inches, they form a sort of open-work Mosaic pavement of many well-toned colors. It was chiefly the larger stones that were turned dark brown with desert varnish. On approaching the creamy playa, we crossed a belt of greasewood bushes; each bush determined the formation of a mound, from 4 to 6 feet high, of wind-drifted material within its branches and for 10 or 20 feet to leeward (N E.). The plain here has in consequence a very different appearance according as one looks up the wind and sees chiefly the white mounds, or down the wind and sees chiefly the green bushes. Some of the mounds were made of fine textured clayey material; others of oolitic grains; the latter were of looser build than the former. We found the playa surface firm and smooth, so that our wagon wheels left only shallow marks; but at one point we saw indications that some earlier travellers had been mired when the playa was wet and soft.

The chief object in crossing the plain to Indian Spring was to get sketches and photographs of the western face of the House range in the advantageous light of the late afternoon, but we were disappointed in this object by reason of a curious dust storm. The morning had been clear. About noon clouds began to form over the House range in the east and over a lower, subdued range in the west; the clouds at first were cumulus of moderate thickness; afterwards a cirro-stratus overflow was added, which turned towards the playa basin from each range. About 5 P. M. the cumulus part of the clouds had almost disappeared and rain trails were seen falling from the cirro-stratus that came from the House range. At the same time clouds of dust were raised beneath the rain trail, apparently around the border of a body of descending, outflowing, and again ascending air. The dusty wind squall passed our camp and made the air so turbid that the mountains were completely hidden for a time; at sunset they were seen only in general outline, without detail.

We rode southward on July 22, crossing the plain west of the playa, where the fine powdery soil, rather plentifully occupied with low greasewood bushes, gave hard work to our horses. After a few tiresome

miles we reached some low isolated limestone ridges in which the northeast strike of the beds, with northwest dip, did not agree with the general north and south trend of the relief. Similar isolated ridges had been noticed north of Indian Spring, and we were led to suppose that all of them belonged together on the crest of an otherwise buried fault block. Shorelines, apparently at the Provo level, were well carved on the ridge slopes; the cut platforms were seldom over fifty feet wide, even where they faced a broad stretch of deep waters in the ancient lake; and this confirms the opinion already expressed that the large terminal facets of the Wasatch spurs cannot have been to any significant extent carved by the Bonneville waves, for the cut platforms would have to be at least a thousand feet broad to match them.

Several sketches of the House range, including figures 19 and 21, were drawn from one of the isolated ridges in the oppressive heat of the afternoon, but clouds and haze again prevented our taking any serviceable photographs. A low range on the western side of the inter-

FIG. 14. — Bevelled upland, west of the southern end of the House range, looking south.

mont basin, some miles to the south, showed an even upland which bevelled its west-dipping strata, as in figure 14, this was one of the few cases in which a form, apparently referable to an earlier cycle of erosion, was recognized. To the west of the isolated ridges and beyond an arm of the basin plain, a long slope or wash ascended gradually into open branching valleys between the sprawling, fading spurs of a subdued and low desert range, which stretched north-northwest from the bevelled upland, figured above. The indefinite baseline in the range trended northwest, while the strike of its west-dipping strata was more nearly north and south, so that one member of the rock series after the other ran obliquely down from the range crest to its frayed-out border and disappeared under the wash. The general appearance of a part of this range, as seen from the western base of the House range two days later, is shown in figure 15, without indication of structure. It seems here as if a peneplain, eroded on west-dipping strata, might

have been uplifted and warped with a moderate slant to the northeast, and then maturely dissected; but this idea is only offered in the way of a suggestion, to be tested by some one who may cross to the western side of this unattractive, waterless range.

In the afternoon we turned eastward across the southern arm of the playa and ascended a great fan, figure 21, to Painters Spring in a ravine at the western base of the granitic part of the House range, Plate 2, A and B. Boulders up to 15 or 20 feet in diameter are common in the lower part of the ravine and at the apex of the fan; some boulders are 10 or 15 feet through at a distance of half a mile from the ravine mouth. The slope of the fan near its head was about 8°. As has been stated already for other fans, the shore lines that are cut on this one are relatively insignificant features; some beaches and south-pointing spits on the piedmont slope a few miles farther north are of larger size. The mouth of Painters ravine is lower now than it was once, as is indicated by old boulders which lie on a rude terrace or bench, some 50 feet above the present channel. Some of the boulders are much weathered; one of them, sketched in figure 16, suggests the skull of a huge pachyderm; it was 9 feet in height. The ravine has a number of good-sized cottonwood trees, 30 or 40 feet high, growing in its bed; hence it may be inferred that no devastating, boulder-bearing flood has swept down the ravine for many years past. The little stream in the ravine was led by pipes to some troughs, built by stockmen, but at the time of our visit there was no stock in the intermont basin, although we saw a number of horses and cattle on the mountain. The stream was not running when we entered the ravine about sunset, but it began to trickle soon after dark, and it ran merrily through the night and the early hours of the next morning, only to dry away again when the sun came over the mountain.

FIG. 15.— A subdued range west of Tule flats, looking west.

The greater part of July 23 was given to a ride southward and back again along the base of the range, crossing several great fans on the

way, and entering some of the ravines to see the relation of the instrusive granite to the limestones. There were several light showers in the early afternoon, drifting northeastward. After their passage we climbed one of the spurs near Painters ravine, whence a fine view was opened along the face of the range. The next day we turned northward, and then crossed the range eastward by the southern of the two roads hereabouts through a low pass. After continuing eastward nearly to the base of the range, we turned southwestward up a dry valley, at the head of which, near the granite, there was a small spring. From this point we walked up to the range crest on July 25, gaining extended views in all directions. Sevier lake was well seen to the southeast. Several good springs occur in the granite part of the highland; they are indicated by copses of bright green aspens, as well as by many well-worn paths of horses and cattle leading to them. The lower valleys were nearly all dry. There are good sized pines and firs on the higher slopes, but many of the trees are dead, and there are few or no young ones to replace them. In the evening we turned back towards Deseret, making a dry camp for the night on the plain in brilliant moonlight. The next afternoon we reached Deseret and there the party disbanded.

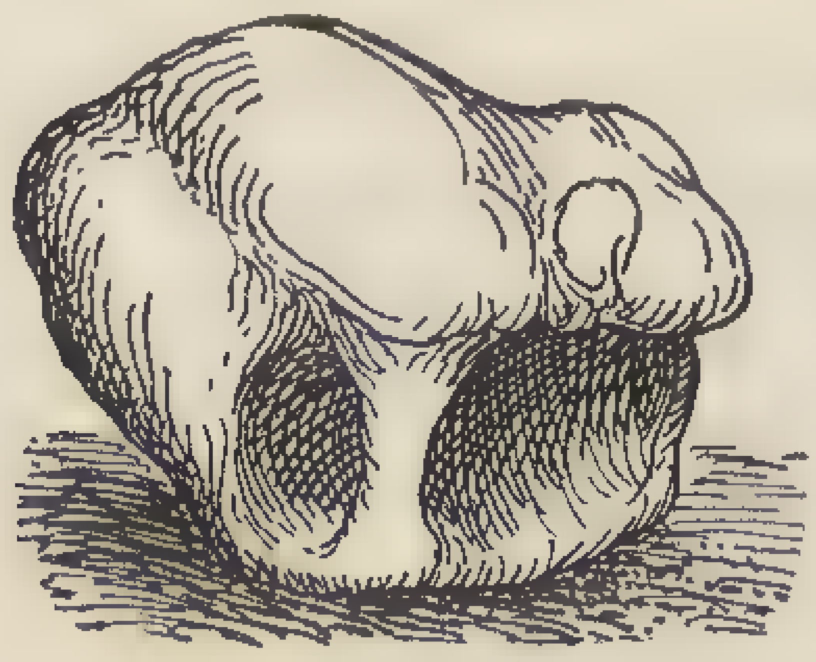

Fig. 16.— A weathered granitic boulder in Painters ravine, House range; height of boulder, 9 feet.

The Structure and Subdivisions of the House Range. Gilbert visited this range in 1902 and gave some description of it at the meeting of the Geological Society of America in Washington in the following winter; but no published account of his observations has yet appeared. The range as thus described seemed to offer so many features characteristic of a typical fault-block mountain, well dissected, that I determined to have a sight of it. As Gilbert's report will include a map by Johnson and a fuller discussion of the rock series and structure than could be made from our brief visit, the present account will be limited to matters bearing particularly on the place that the range should have in a systematic classification of mountains.

The range trends north and south, with a length of forty or fifty miles and a breadth of ten or twelve. As a whole it is an east-dipping monocline of palaeozoic strata, presenting a moderate slope to the east and a strong escarpment to the west. There is a large intrusion of granite in its southern part. The highest summit, Swazy peak, rises next north of Antelope Spring, near the middle of the range; the desert basins on

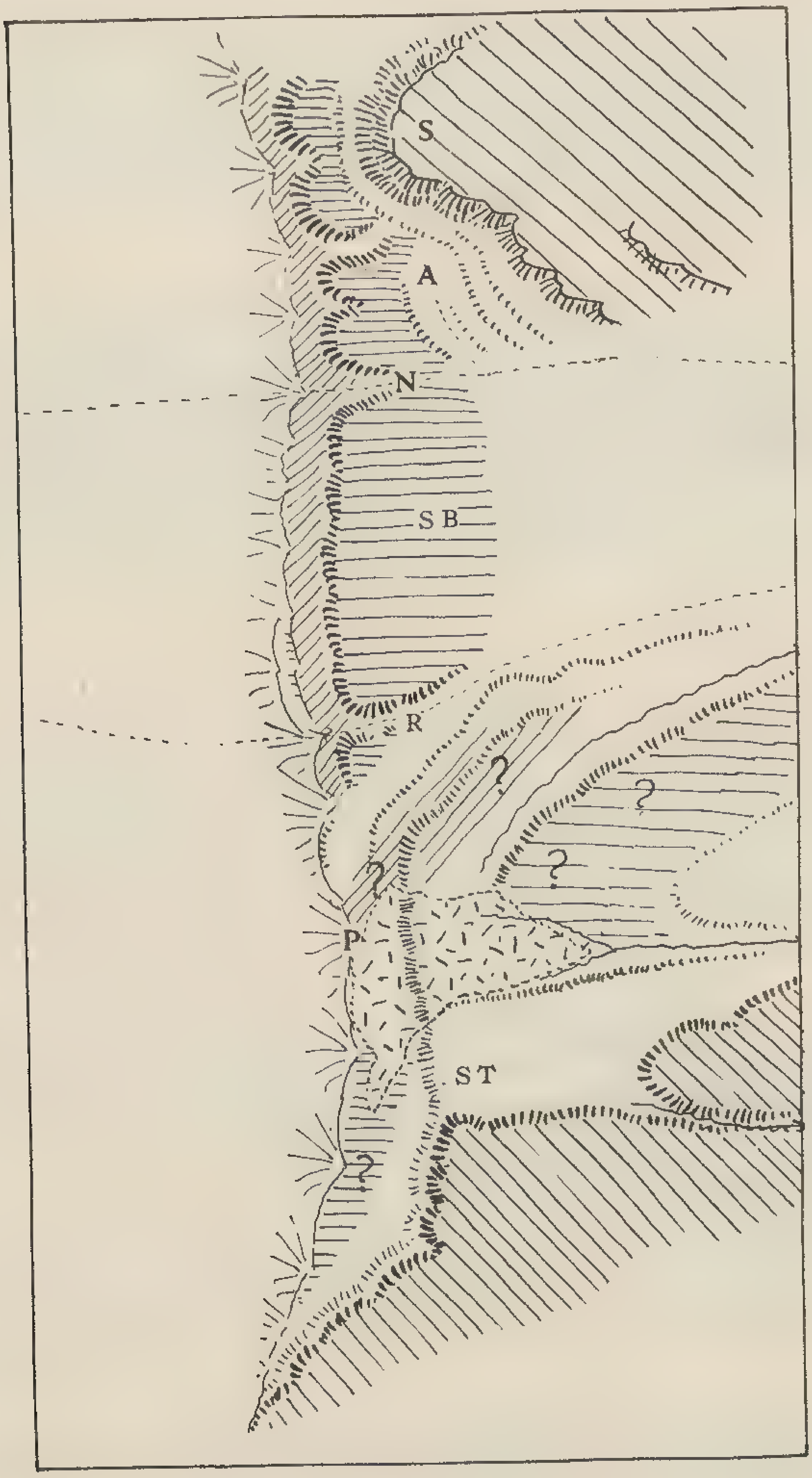

FIG. 17.—Rough map of the part of the House range: scale, about 4 miles to an inch.[1]

[1] S, Swazy peak ; S. B. Smoothback mass; S. T., Sawtooth mass. Lines slanting to right, upper gray limestones ; horizontal lines, gray-and-slate-colored lower limestones ; lines slanting to left, quartzites. A, Antelope Spring ; N, pass of northern road ; R, pass of southern road ; P, Painters Spring. The playa of Tule flats lies to the west of the range.

the east and west have an elevation of between 4,500 and 5,000 feet. When seen from the Sevier desert on the east, the crest of the southern part of the range shows some rather strong knobs, from which it has been called the Sawtooth range; this name will here be used for the quarter of its length that lies south of the southern of the two roads by which it is crossed. The next quarter, rather a short quarter,

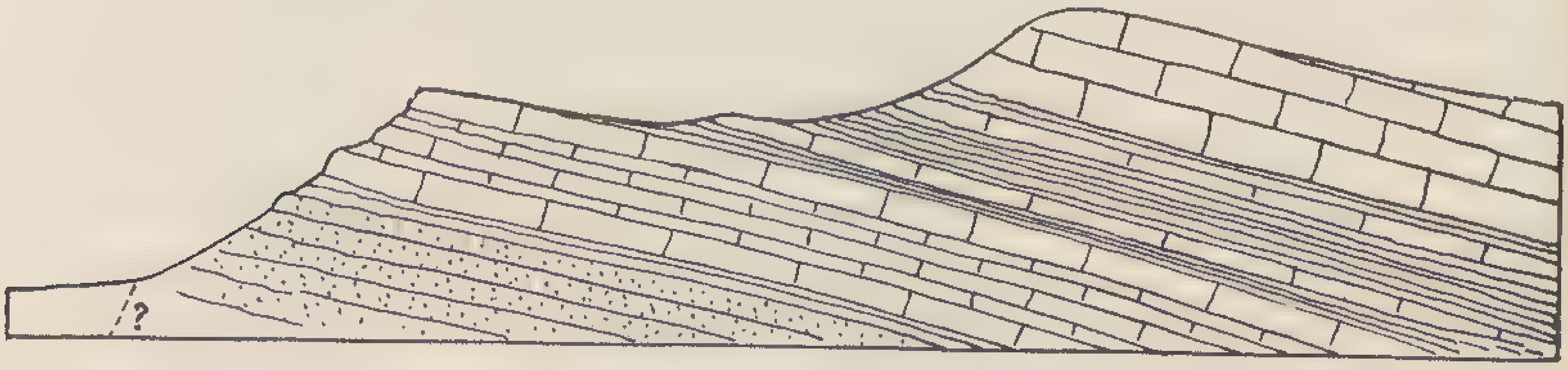

FIG. 18.— East-west section of the Swazy mass, looking north: length of section, about 5 miles.

indeed, lies between the two roads; it has an even crest and a simpler back slope than the rest of the range; this part will therefore here be designated by a provisional name, the Smoothback mass, because of its freedom from deep ravines by which the eastern slope of the range is elsewhere dissected. Then comes the Swazy mass, north of which our excursion did not reach. The parts of the

FIG. 19.— The south end of the Smoothback escarpment, showing the notch by which the southern road ascends to the oblique transverse depression that is worn on the Trilobite shales; looking east.

range here referred to are shown on the rude map of figure 17.

The lowest beds that we saw along the base of the western escarpment were chiefly dull reddish quartzitic strata, several hundred feet in thickness; these were followed by a great body of limestones with some shales near their middle; the lower limestones make gray-and-

slate colored cliffs in the escarpments of the Swazy and Smoothback masses, the middle members are largely shales, containing Agnostus and Discina, and the upper members are strong grayish limestones which form Swazy peak and (if our identifications are correct) the knobs of the Sawtooth range. The total thickness of the series must be 4,000 or 5,000 feet at least. With more time for observation, this

FIG. 20.— Looking southward across part of the granitic highland of the Sawtooth mass to one of the escarpments of the overlying strata (middle shales). The escarpment of the upper gray limestones is in the distance on the left.

rough statement of the rock series might have been greatly refined; as it stands it is undoubtedly open to corrections from whoever can examine the range more thoroughly.

The Swazy mass is a simple monocline, dipping eastward 5° or 10°, as illustrated in figure 18. The gray-and-slate colored limestones make the bold promontories west of the peak and as far northward as

FIG 21.— The western escarpment of the Sawtooth mass, with ragged granitic spurs and the great fan of Painters ravine in the center. The cliffs of the upper gray limestones descend from the cliffed peaks southward (to the right).

we could trace them from a good view point. Here and far to the north the eastward dip of the strata might account for the north-south trend of the range, for its bold west-facing escarpment, and for its moderate eastward slope, under the action of long continued erosion alone and without block faulting, provided that a body of weak

strata occurred beneath the harder strata which cap the escarpment; but we found no sufficient indication of such weak strata, for the base of the escarpment is made chiefly of quartzitic beds which stand out in abundant outcrops.

The Smoothback mass is also a simple east-dipping monocline for the most part, but on its southern side a dip of 15° or 20° to the southeast is developed; and as a result the gray-and-slate colored cliffs which crown the escarpment along this quarter of the range, as well as farther north, descend to the mountain base at the north end of the Sawtooth mass, and the Trilobite shales make an oblique, northeast-southwest depression across the range between its two southern quarters and open a broad gap in its western face. Curiously enough, a sharp notch is cut east and west into the descending part of the gray-and-slate escarpment, shown in front view in figures 19 and 22, and

FIG. 22.— General view of the western escarpment of the Sawtooth mass. The piedmont fans (somewhat exaggerated in size) have Bonneville shorelines and

in side view in Plate 3, A, and in figure 25; and through this notch the southern of the two roads ascends from the basin of Tule flats to the oblique depression and pass formed by the Trilobite shales. The notch and the absence of the upper limestones from the Smoothback mass are peculiar features, not to be explained by a one-cycle carving of a simple monocline, but easily explained by erosion in two cycles.

The Sawtooth mass continues the southeast dip which began on the southern side of the Smoothback mass, and as a result the scarp-making edges of the harder layers here run obliquely across the back slope of the range: they may be easily traced from their first appearance low down at the eastern base, through their gradual ascent southwestward to the range crest, although they are more or less interrupted by deep valleys. About the middle of this mass intrusive granite replaces the stratified series over several square miles of highland, as shown in figure 20, and occupies part of the western escarpment, as

in figure 21 (see also figure 17, and Plate 2, A, B); yet it causes very little disturbance in the monoclinal attitude of the layers. The southern end of the range seems to be determined by a somewhat steeper dip, whereby the resistant limestones that make the teeth of the saw descend with the crest of the range to lower and lower levels; but we did not go far enough southward to determine just how the termination of the range is brought about. In consequence of this southeastward dip, the western escarpment of the Sawtooth mass gives an oblique section of the rock series which is of great significance, as will be more fully stated below. The general features of this escarpment are shown in figure 22, in which several sketches from different points are combined, thus giving the effect of a more distant view than was really taken. The fans are somewhat over-large for the height of the range.

notch of the southern road on the left; the end of the range on the right. The spits built on their southern side.

There is some indication of a transverse fault between the Swazy and Smoothback masses, for on viewing their escarpments from the playa on the west, the gray-and-slate colored cliffs which cap the promontories of the Swazy mass and the more continuous escarpment of the Smoothback mass do not seem to stand in the same plane; the southern seems to be several hundred feet lower than the northern, and the displacement apparently lies somewhat north of the ravine by which the northern road descends to the playa. Some local indications of such a displacement, with the downthrow on the south, were noted as we came down the road in the ravine; an isolated knob north of the road had its cliff-making strata at apparently the same level as those on the south of the road, but lower by some 200 feet than the corresponding strata in the next spur farther north, as in figure 23. The termination of several ridges on the eastern slope a little north of the northern road also suggests that they are prevented from continuing farther south by a transverse fault.

There is evidence of a still stronger transverse fault in the northern part of the Sawtooth mass, for after the heavy gray-and-slate colored limestones of the Smoothback mass have pitched southward and disappeared, the next strata farther south, just before the granite is reached, are reddish quartzitic beds, which elsewhere were noted only beneath the limestones. Unfortunately we had not time to make a careful northwest-southeast section across the questionable district, by which such a fault could be easily determined.

The West-facing Escarpment of the House Range. The range thus described is believed to be a tilted and dissected fault block, chiefly because its western escarpment and baseline are comparatively continuous and of moderate curvature, although they traverse a variety of structures; and because a number of rock masses, peculiarly de-

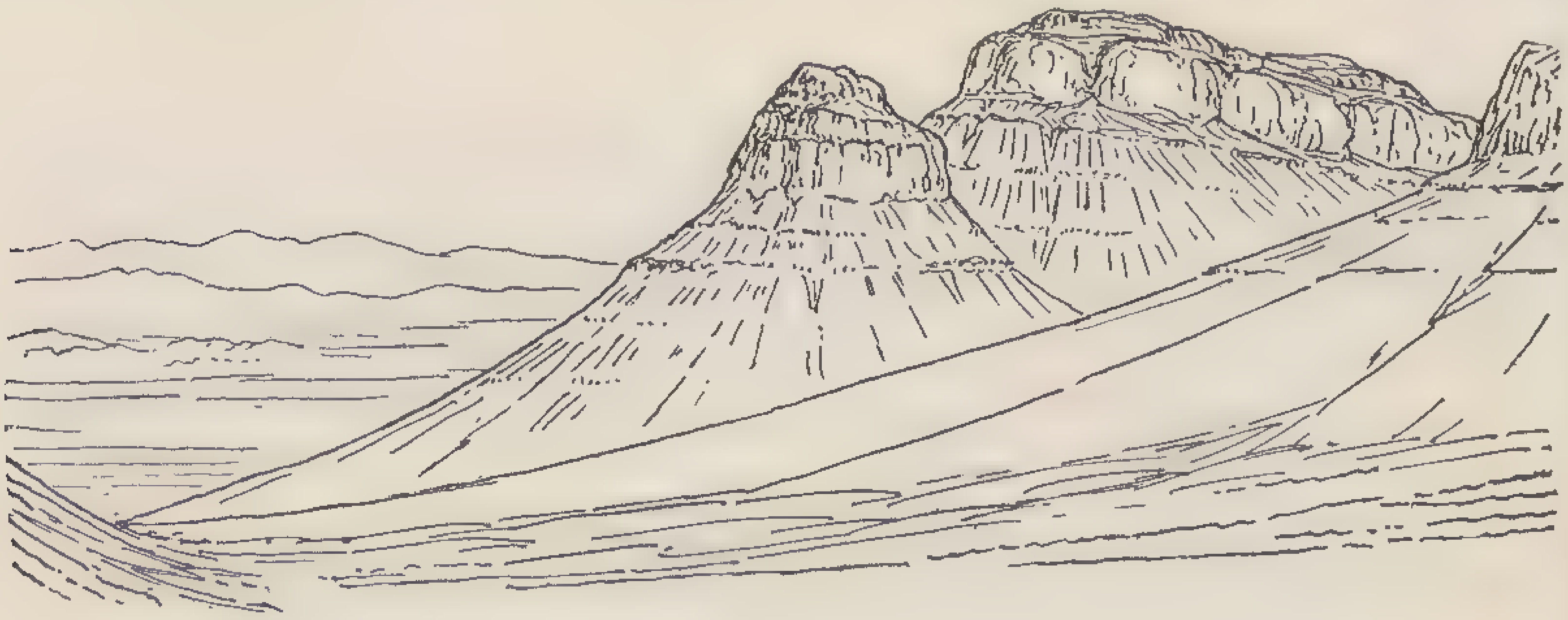

Fig. 23.— Displaced knob of gray-and-slate limestones, in the notch of the northern road; looking northwest; Tule flats and the Deep creek range in the distance.

formed and out of place, occur in the piedmont slope beneath the escarpment. The dissection of the fault block has progressed much farther than the dissection of the Wasatch range, and about as far as that of the Canyon range.

With regard to the west-facing escarpment, it might, as already suggested, be explained in the Swazy mass as the normally retreating face of a monoclinal structure which once extended much farther westward, provided that a series of sufficiently weak strata was found along its base. But if this were the true explanation, the escarpment should persistently follow the strike of the cliff-making limestones; it should turn to the southwest at the southern part of the Smoothback mass, where the dip changes from eastward to southeastward. Similarly, the strata in the strong northeast-southwest escarpment, by

which the northern border of the Sawtooth mass overlooks the oblique depression along the southern side of the Smoothback mass, should continue their course far to the southwest across the intermont basin, instead of being cut off obliquely about in line with the termination of the cliffs in the Smoothback mass, as in figure 22 (left end). Likewise the heavy limestones that form the high knobs of the Sawtooth mass should continue with full height southwestward along their strike, instead of obliquely descending the face of the range to the basin level and ending in line with their truncated fellows. Far from exemplifying the well determined laws that correlate the structure and the form of folded and normally eroded mountain masses, the various resistant members of the House range are all arbitrarily terminated on the north-south line of the west-facing escarpment; hence the escarpment cannot be reasonably regarded as the result of normal retrogression of a once much larger monoclinal mass; the termination of the strong mountain-making strata can be explained only by block faulting of a comparatively recent date. The oblique truncation of the rock series in the southern part of the range is therefore highly significant, and its explanation carries with it the explanation of the simpler escarpment farther north.

The continuity of the escarpment across the granitic part of the Sawtooth mass is less significant than was supposed when the granite was first seen in the distance; for a closer examination showed that the granite did not generally come forward to the face of the mountain, but was bordered by certain members of the normal series along the base of the range, as in Plate 3, B. Still several branches of the granite intrusion do come out to the base of the range and instead of making spurs are there terminated in line with the bedded rocks among which they are intruded.

Whether the transverse faults near the two cross roads are finally shown to exist or not, and whether, if proved to exist, they are of remote or of comparatively recent date are matters that do not bear on the problem here discussed; for the fault that is inferred along the western base of the range may cut older faults just as easily as it may cut older folds or monoclines or strata of any attitude.

The displaced rock masses along the western or faulted base of the range are of importance. Several examples may be noted. One was seen at the western base below the high promontory west of Swazy peak, as sketched in figure 24; it should be compared with the more normal section in figure 18. A short distance south of the northern road an outcrop of gray limestone with a westward dip of 35° was seen

in the piedmont slope beneath the quartzitic series. Along the base of the southern part of the Smoothback escarpment, there is a piedmont ridge a mile or more in length, consisting of quartzite and limestone, apparently with normal dip, but much below the normal position, as in figure 25 and in Plate 3, A. Finally there are some low spurs below the northern end of the Sawtooth escarpment, two or three

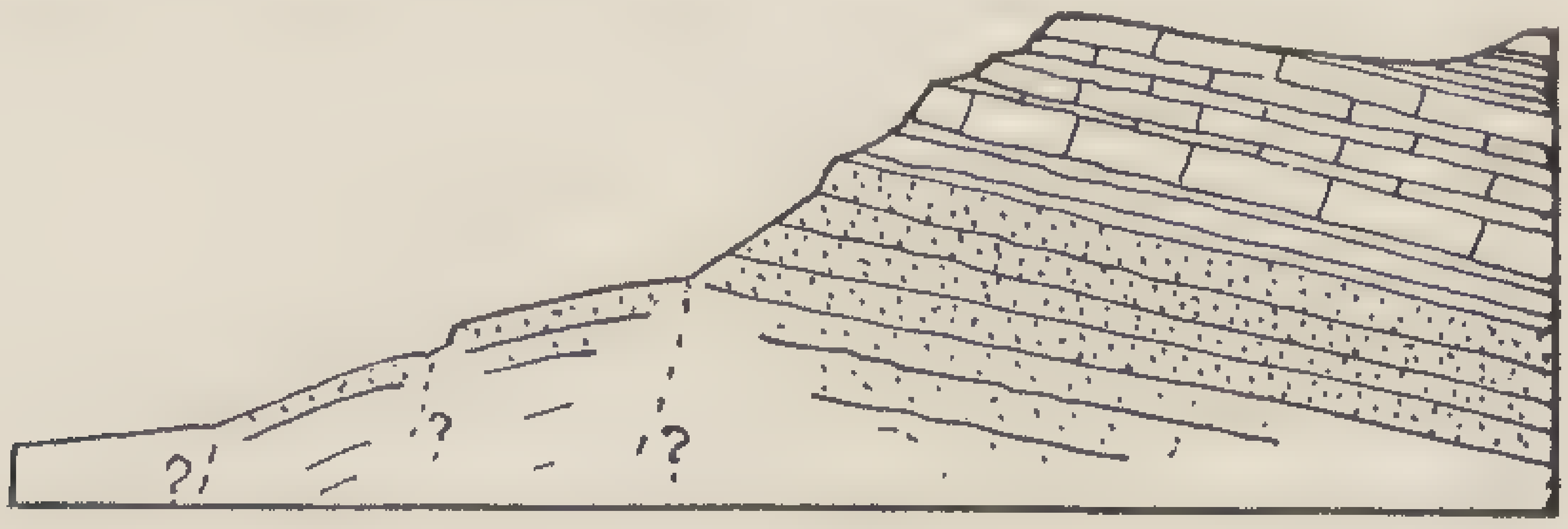

Fig. 24.— Displaced strata at the base of the western escarpment, Swazy mass; looking north.

miles north of Painters ravine, where layers of limestone of unknown position in the series dip to the northwest at moderate angles. When the general regularity of the monoclinal structure in the range is recalled, with prevalent dips to the east and southeast, it becomes all the more significant that the several cases of westward dips are found in narrow belts of displaced layers along the western base of the range,

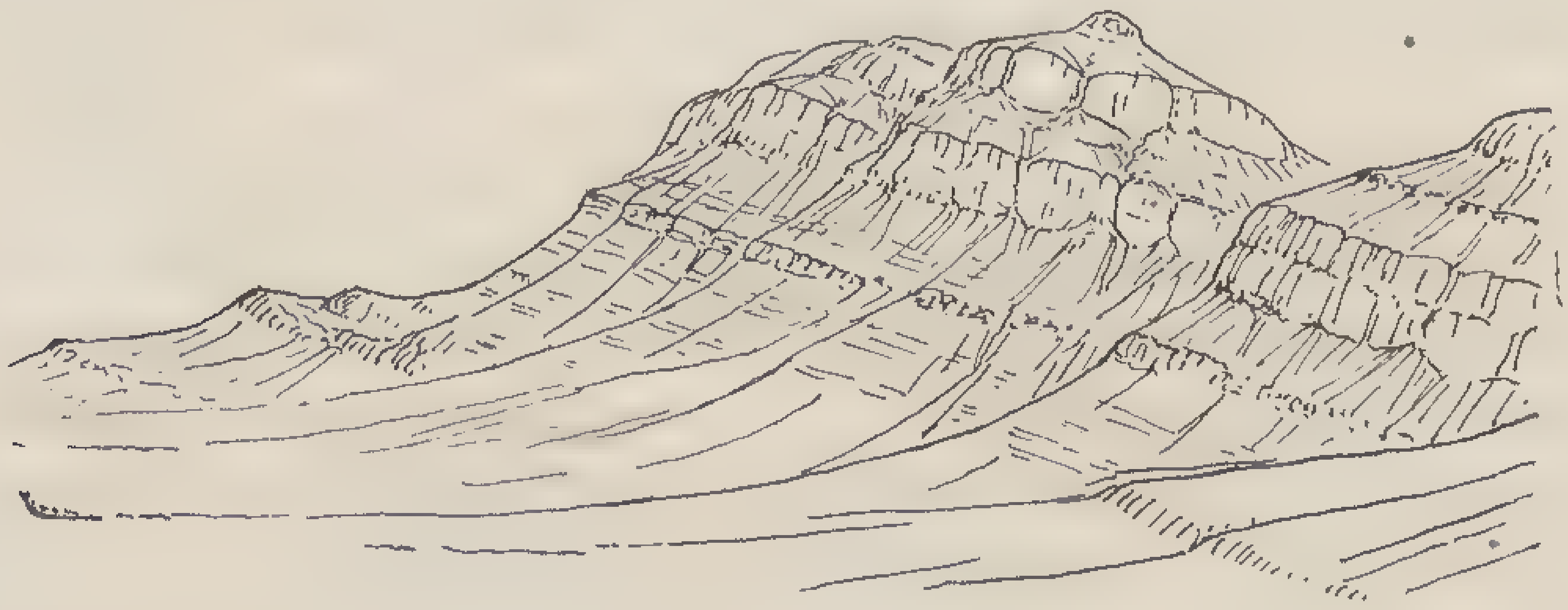

Fig. 25 — The southern end of the Smoothback escarpment, with displaced strata at its base; view looking north past the notch of the southern road.

where the occurrence of a great fault is clearly indicated by independent evidence.

In view of all this it may be fairly said that the essential consequences of the fault-block theory of the Basin ranges are successful in meeting the appropriate facts with which they are here confronted, and that the theory is worthy of acceptance, so far as House range is

concerned. The uplifted block has, as a natural accompaniment, an associated depressed block, now buried under the detritus of the adjacent intermont trough. The trough or basin of Tule flats, west of the House range, is an excellent counterpart of the range itself.

The amount of displacement by which the House range block was set in relief is not closely determinate, because the corresponding strata in the depressed block under Tule flats are not to be seen; but a measure of 3,000 feet may be given as a minimum.

Post-faulting Erosion of the House Range. The erosion that the House range has suffered since the last faulting and uplift of its block is very much greater than the corresponding erosion of the Wasatch range. The base of the House range escarpment is not marked by any faults across its detrital fans. The great promontories and spurs into which the face of the Swazy escarpment in particular is carved have no distinct truncating facets at their base. The crest of the escarpment in general must have retreated the greater part of a mile from the fault face. The valleys between the spurs have somewhat opened mouths. The back slopes of the Swazy and Sawtooth masses are deeply carved by many valleys. If the range shows more ungraded cliffs than are seen in the Spanish-peak Wasatch, for example, this feature must be ascribed to the repeated alternations of hard and soft layers, and not to early youth. Yet the erosion of the faulted mass must reach at least twice its present large measure before the evidence of faulting, based on the oblique truncation of the heavy limestones by the west-facing escarpment, is seriously impaired.

An appropriate consequence of the advanced erosion of the uplifted block is the great size of the fans at the foot of the escarpment. It is evident enough from the small share that the Bonneville waves have had in modifying the fans that the climatic conditions which led to the formation of large lakes in the intermont depressions were brief and recent episodes in the post-faulting history of the range, and that a climate like that of today has been characteristic of the region as far back as climatic conditions can be inferred.

Pre-faulting Erosion of the House Range. An interesting problem is opened by the search for remains of forms that were produced by erosion in the pre-faulting cycle and that have not yet been entirely obliterated by the erosion of the post-faulting cycle. It is evident that such forms are limited to the back slope of the tilted block. They had their origin in the first of the three chapters into which any problem of the kind here treated is naturally divided: a first cycle of erosion, involving the structure, erosion and form of the pre-faulting period;

the faulting, by which the first cycle was interrupted; and a second or post-faulting cycle of erosion, producing the forms of to-day. The Swazy and the Sawtooth masses are of special interest in these respects, since they both possess features that cannot be reasonably accounted for by post-faulting erosion, or by erosion in a single cycle uninterrupted by faulting, and yet which are very reasonably accounted for by pre-faulting erosion. The features of the southern mass will be considered first.

The oblique course of the scarp-making layers on the back slope of the Sawtooth mass has already been mentioned. The northernmost scarp, which overlooks the valley worn on the Trilobite shales, may be in some way related to the fault that is supposed to divide the two southern masses; the other scarps, especially the one formed on the uppermost gray limestone, are purely the work of retrogressive erosion. Their course is only locally interrupted by the granitic intrusion and

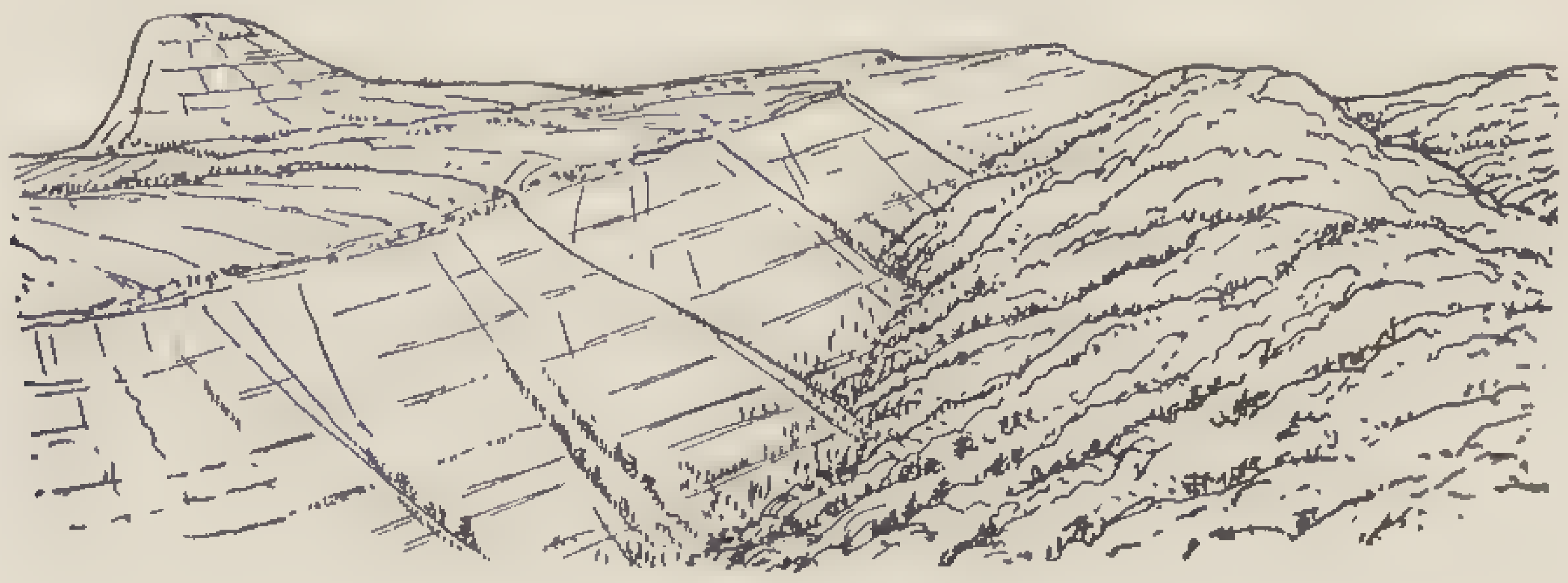

Fig. 26.— Valley along the contact of intrusive granite and middle shales (?) in the highlands of the Sawtooth mass; looking west.

by the valleys of the back slope. On the whole they maintain their oblique ascent of the range in rather regular order, as indicated in figure 17. The escarpment of the middle layers facing northward towards the granite is shown in figure 26. Three suppositions may be made in explanation of these features: — a single southeast-dipping monocline, long eroded in a single cycle, without further disturbance by tilting or faulting; a southeast-dipping monocline, long ago cut in two by a north-south fault and the eastern block uplifted with an eastward slant before much erosion of the monocline had been accomplished; the same, but with subrecent faulting and uplift after much erosion of the monocline. The second and third cases differ from the first in involving two cycles of erosion, instead of only one; they differ from each other in that the second case postulates a short first cycle and a long second cycle, while the third case postulates a long first cycle and a short second cycle.

The case of the simple monocline eroded in a single cycle will be first considered. If the present southeast dip of the strata in the Sawtooth mass were the result of a single deformation, long acted on by normal erosive processes, a series of ridges and valleys trending northeast and southwest would be the inevitable result, and these features would continue as far as the longitudinal extent of the monocline; the general altitude of each ridge in a late stage of erosion would depend on the resistance of its strata; notches and water gaps might be cut here and there, but no persistent increase of height in one direction for ten or more miles could be expected. On turning to the observed facts, it is evident that they strongly contradict these consequences of a single cycle of erosion. The ridges or scarped edges of the harder layers die away at the eastern base of the range, although there is no indication that the monocline terminates there; it has every appearance of being continued under the gravels of the eastern piedmont slope, which are indeed interrupted here and there by undetermined mounds for some distance out towards the Sevier desert plain. To the southwest, the scarps are sharply cut off in the fine escarpment of the range; and between these two unlike endings they show a gradual increase in height, locally interrupted by notches and valleys. The supposition of a single cycle of erosion is therefore altogether inadequate to explain the facts.

In the second case, if the fault block of monoclinal structure were uplifted with an eastward slant before much erosion of the preexisting monocline had been accomplished, then the recession of the various ridges or scarp-making layers from the crest of the block must have been effected since the faulting. Such a recession might well result in due time in the formation of a number of ridges on the back slope of the block, but each ridge should then continue its course far northeastward to the end of the block along the strike given to its strata by the combined movements of the two periods of deformation. As a matter of fact the back-slope ridges in the Sawtooth mass run obliquely down from the crest of the range to its eastern base and there fade away. Hence the supposition of faulting before the pre-existent monocline was much eroded is also unsatisfactory.

In the third case, if the southeast-dipping monocline were much eroded before the north-south block faulting occurred, then the back slope of the tilted block should be obliquely ascended by belts of hard and soft strata, sculptured into appropriate relief; and these oblique features would be altogether destroyed only after much ero-

sion of the uplifted block. The peculiar consequences of the third supposition accord so well with the facts of observation that the supposition is warranted.

It must therefore be concluded that the district of the Sawtooth mass was reduced, in a cycle of erosion before the block faulting, to a series of monoclinal ridges and valleys of moderate relief, the general series of trends being about northeast and southwest, and the drainage being adjusted to the structure in longitudinal and transverse courses. Since the opening of the second cycle of erosion by the upfaulting of the mountain block, the fault face has been deeply carved and the back slope has gained a greatly increased relief in the incision of many valleys, most of which seem to result from the revival of the preexistent adjusted streams; but the oblique course of the strata on the back slope still persists in the general pattern of the first cycle.

One curious feature deserves special mention here. The knobs or teeth from which the Sawtooth range gains its name are formed of the

FIG. 27.— The knobs of the Sawtooth mass, looking south.

uppermost limestone, where its scarp reaches the crest of the block. Seen from the eastern side, the teeth are round and dull; but on the western face they have been cut sharp in huge vertical cliffs at the head of deep ravines. The contrast of the two slopes is very striking; it can be seen to advantage only from the crest of the range itself, north of the teeth, where both their sides are visible, as in figure 27.

The history of the Swazy mass may be more briefly sketched. The eastward dip of the strata in this part of the range is but little greater than the eastward dip of the block itself. Before the faulting occurred, the strata must have been nearly horizontal. In a district of truly horizontal strata, the result of prolonged erosion would be the production of irregular and relatively systemless escarpments. In a district of gently dipping strata extensive erosion might produce some general alignments, but the alignments would have a considerable

irregularity and many irregular valleys would be eroded in the higher strata. If we now turn to the facts it is found that the higher gray limestones of Swazy peak have a border that pays little attention to the scarp of the fault block. The border of the higher limestones stands well to the west in the peak, which rises only two or three miles back from the face of the range; the border recedes southeastward (and probably northeastward also) on the flanks of the peak, and nearly reaches the eastern base of the range by the northern road. The slopes of the range east of the peak are irregularly dissected by valleys that show basset edges, as in figure 28, with unusual frequency.

These features suggest very strongly that the general outline of the upper limestones must have been determined by extensive erosion in the earlier cycle, before block faulting occurred. The gray-and-slate colored limestone, on the other hand, advances to the great promontories of the Swazy mass, and these promontories stand in so accordant a relation to the western base of the range that it must be supposed they were determined by post-faulting erosion. It is satisfactory to note that these conclusions accord with those gained from the features of the Sawtooth mass. For the present, Swazy peak has generally graded slopes; but when the ravines of the western escarpment are gnawed farther back into the range, some of them will undercut the base of the peak and sharpen it into huge cliffs that may outrival those already sharpened in the Sawtooth mass.

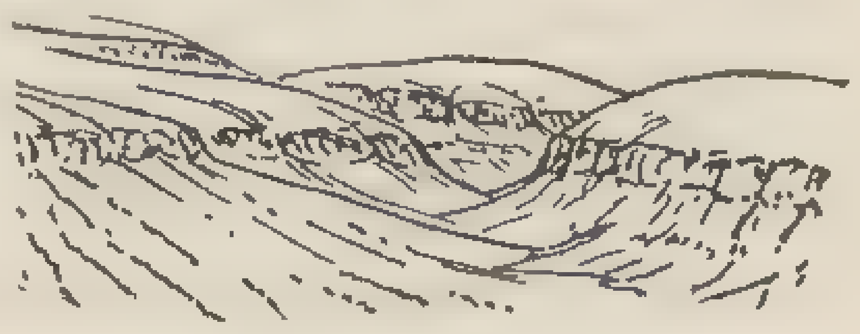

FIG. 28.— Valley in the back slope of the Swazy mass, with basset edges and ordinary outcrops; looking north.

The absence of the upper gray limestones from the eastern slope of the Smoothback mass cannot be accounted for by erosion during the relatively short part of a cycle that has elapsed since the block faulting, but it may have been accomplished naturally enough in the pre-faulting cycle. In such a case the Smoothback area may then have been a peneplain underlaid by the more or less shaly intermediate members of the rock series. Since the block faulting the shales have been mostly swept off, leaving a rather smoothly stripped back slope, from which this part of the range is given its provisional name.

General Considerations.

If the conclusions now reached are taken to apply to the Basin ranges as a whole, the following general statement may be made. The region appears to have reached a stage of late maturity or early

old age in a cycle of erosion that was introduced by a relatively remote and wide-spread deformation. The low ranges with sprawling, fading spurs and wide open valley mouths are regarded as the residual reliefs of the earlier cycle, undisturbed or only slightly disturbed by the later faulting, and not greatly modified by continued erosion. The high ranges, with strong slopes, simple base lines on at least one side, and relatively narrow valley mouths, are regarded as uplifted and tilted blocks of the previously eroded region, now well entered upon a new cycle of erosion. The intermont depressions, more or less aggraded, appear to be relatively depressed areas, now covered with waste from the higher areas; but the possible occurrence of bevelled rock floors at a small depth beneath the waste slopes of the low ranges must not be overlooked, especially where the waste slopes extend far up towards the low mountain crests.

Gilbert has explained the Basin ranges essentially as tilted blocks; his original account gave much attention to the faulting of the mountain blocks, little attention to their pre-faulting structures, and still less attention to the pre-faulting and post-faulting erosion that they have suffered. Spurr has more recently explained the Basin ranges without regard to block faulting, as the result of "compound erosion," that is, of a long continued series of deformations and associated erosions, but without attempting to specify the sequence, the dates or the relative values of the processes concerned. Thus stated the two explanations of the Basin ranges seem incompatible.

Gilbert's later discussion of the Basin range problem, in the oral presentation of his paper at Washington, as above stated, takes fuller account of the three chapters that his theory suggests; namely, the pre-faulting structure and erosion, the faulting of the mountain blocks, and the post-faulting erosion. His conclusions are well supported by Louderback in a recent Bulletin of the Geological Society of America, concerning an isolated range in the Great basin, in which it is clearly shown that the pre-faulting deformation was followed by so long a period of erosion as to reduce the district to a surface of small relief, which was then covered by a lava sheet; that a block of the compound mass was then uplifted with a tilt to the eastward; and that later erosion has not yet accomplished extensive dissection of the tilted block. In this case, the term, monoclinal block, is justified by the attitude of the tilted lava sheet, but not by the disordered structures beneath it.

The incompatibility between Gilbert's and Spurr's explanations disappears if the various factors of Spurr's compound erosion are given specific values. Modern faulting is not excluded from these

factors; it may therefore be introduced wherever it is demanded by good evidence. Without the aid of modern faulting, compound erosion cannot account for the forms that certain of the higher Basin ranges possess. No combination of deformations and erosions from which strong modern faulting is omitted can produce strong ranges in close relation to broad intermont basins, such as I have seen in the House range of Utah and the Stein mountains of Oregon, to say nothing of various smaller ranges or of the long Wasatch range on the eastern border of the Great basin.

The attribution of specific dates and values to a compound series of processes, in order more fully to explain the observed details of mountains structure and form, may be regarded as a refinement of geological and physiographical study corresponding to that which is made when qualitative work in chemistry is carried forward to the quantitative stage. It is this refinement that in my opinion places Gilbert's discussion of the Basin ranges in advance of Spurr's.

Frequent mention has been made in the preceding pages of uplifted mountain blocks. One member of our party expressed some dissent from the view of problem thus implied, and preferred to regard the mountains as relatively quiescent areas, and to regard the intermont troughs as depressed "graben." As far as the locally observed facts are concerned, it would be difficult to make absolute choice between these two alternative forms of statement and the processes that they represent. The only safe statement appears to be that differential movement has taken place. Any sort of dislocation that satisfies this requirement deserves consideration. The whole region may have been uplifted, the mountain blocks more than the trough blocks; the whole region may have been depressed, the trough block more than the mountain blocks; the mountain blocks may have been uplifted while at least some of the trough blocks stood still; the trough blocks may have been depressed while at least some of the mountain blocks stood still; the mountain blocks may have been uplifted by various amounts and the trough blocks depressed by various amounts. Until some sufficient means for discriminating among these various possibilities are gained, it seems best to maintain an open mind regarding all of them. The meaning of "uplifted block," as here used, is therefore simply that the block is now exposed to deeper erosion than it was before the "uplift" took place.

There are certain features of the region described in these pages that stand forth in my memory of the excursion as of particular interest and value. One is the maturely dissected landslide on the western

side of the maturely dissected Canyon range; this is a sort of curiosity, not of compulsory value regarding block faulting, yet quite compatible with such an origin for the range, and not reasonably connected with any other origin. Another is the oblique course of the scarps on the back of the Sawtooth mass; these are not conspicuous features and their full meaning was not recognized at first; but it gained increasing force the more they were considered. The tamer forms of the subdued ranges west of Nephi and beyond the Tule flats should not be forgotten, for they are useful foils to the stronger forms of the higher ranges. But pre-eminent above all the rest are the obliquely truncated mountain fronts of the Nebo Wasatch north of Nephi, and of the Sawtooth mass in the House range. The diagrammatic manner in which the hard and soft strata in the monocline of the Nebo Wasatch, figure 4, are cut off at the mountain base, with the modern fault scarp at the foot of the facetted spurs and the recent small landslide where the base line crosses the weakest layers, give this example the rank of a standard type for its class. Yet no less important are the corresponding but more maturely sculptured features of the Sawtooth escarpment, figure 22, in the House range. This is beautifully seen from the highest Bonneville beach on a fan opposite the ravine that has undercut and sharpened the Sawtooth cliffs, and although thus seen only during a short rest on a hot day in the desert, the mental picture of it remains as a distinct and greatly prized memory.

EXPLANATION OF PLATES.

PLATE 1.

A. Facetted Spurs at the western base of the Spanish peak Wasatch range.
B. Lookng north from near Oak city along the western side of the Canyon range, to the great landslide in the middle distance.

PLATE 2.

A. The intrusive granites in the western escarpment of the Sawtooth mass, House range.
B. Painters ravine in the intrusive granite of the Sawtooth mass.

PLATE 3.

A. Looking north to the southern end of the Smoothback escarpment. The notch followed by the southern road is in the center; displaced strata are seen at the base of the escarpment on the left.
B. Sills of intrusive granite among the lower members of the stratified series, south of Painters ravine, western face of the Sawtooth mass.

A. FACETTED SPURS SPANISH PEAK.

B. WESTERN SIDE OF THE CANYON RANGE.

A. INTRUSIVE GRANITES, HOUSE RANGE.

B. PAINTERS RAVINE.

A. SMOOTHBACK ESCARPMENT.

B. INTRUSIVE GRANITE SAWTOOTH MASS.

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A. AGASSIZ. V.[5] General Report on the Expedition.
A. AGASSIZ. I.[1] Three Letters to Geo. M. Bowers, U. S. Fish Com.
A. AGASSIZ and H. L. CLARK. The Echini.
F. E. BEDDARD. The Earthworms.
H. B. BIGELOW. The Medusae.
R. P. BIGELOW. The Stomatopods.
S. F. CLARKE. The Hydroids.
W. R. COE. The Nemerteans.
L. J. COLE. The Pycnogonida.
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C. R. EASTMAN. The Sharks' Teeth.
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H. J. HANSEN. The Schizopods.
S. HENSHAW. The Insects.
W. E. HOYLE. The Cephalopods.
C. A. KOFOID. III.[3] The Protozoa.
P. KRÜMBACH. The Sagittae.
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H. LUDWIG. The Holothurians.
H. LUDWIG. The Starfishes.
H. LUDWIG. The Ophiurans.
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JOHN MURRAY. The Bottom Specimens.
MARY J. RATHBUN. The Crustacea.
HARRIET RICHARDSON. II.[2] The Isopods.
W. E. RITTER. IV.[4] The Tunicates.
ALICE ROBERTSON. The Bryozoa.
B. L. ROBINSON. The Plants.
G. O. SARS. The Copepods.
H. R. SIMROTH. The Pteropods and Heteropods.
TH. STUDER. The Alcyonaria.
T. W. VAUGHAN. The Corals.
R. WOLTERECK. The Amphipods.
W. McM. WOODWORTH. The Annelids.

[1] Bull. M. C. Z., Vol. XLVI., No. 4, April, 1905, 22 pp.
[2] Bull. M. C. Z., Vol. XLVI., No. 6, July, 1905, 4 pp., 1 pl.
[3] Bull. M. C. Z., Vol. XLVI., No. 9, September, 1905, 5 pp., 1 pl.
[4] Bull. M. C. Z., Vol. XLVI., No. 13, January, 1906, 22 pp., 3 pls.
[5] Mem. M. C. Z., Vol. XXXIII., January, 1906, 88 pp., 96 pls.

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POST-PLEISTOCENE DRAINAGE MODIFICATIONS IN THE BLACK HILLS AND BIGHORN MOUNTAINS.

By George Rogers Mansfield.

With Four Plates.

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No. 3.— *Post-Pleistocene Drainage Modifications in the Black Hills and Bighorn Mountains.*

By George Rogers Mansfield.

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Introduction.

In the summer of 1904 the writer spent five weeks in the Black Hills and Bighorn Mountains, as a member of the Harvard Summer School of Geology under the direction of Professor T. A. Jaggar, Jr. About two weeks were spent in investigations of a general nature, while the remaining time was devoted to the study of a special problem in the two fields indicated. The portion of the Black Hills studied (Plate 2) is roughly twelve to fifteen miles in diameter and has for its center a point on Boulder Creek about four miles northeast of Deadwood. The Bighorn district (Plate 4) occupies the front slope and foot-hills of the eastern flank of the mountains, in the immediate vicinity of Big Goose Creek and about fifteen miles southwest from Sheridan, Wyo-

ming. The problem selected was of such a nature that its study could be pursued profitably in both regions. The results of the investigation are embodied in the following pages. In the preparation of the paper I have been greatly aided by the use of specimens, maps, and other data, kindly placed at my disposal by Professor Jaggar.

The Problem Outlined.

In both districts, high above the present water courses, occur extensive deposits of gravels that are apparently of fluviatile origin. In some cases their distribution suggests that they have been laid by the streams of today, before the latter cut to their present depths; but in other cases the gravels are so disposed that they bear little relation to the channels of the water-ways now found in the region and show that considerable changes of drainage have taken place since they were deposited. The slopes of many of the valley sides indicate more than one period of incision. The upper slopes are fairly gentle and seem to be related to the high level gravel deposits and to certain abandoned saddles in the divides, which appear to be of stream origin. The lower slopes are steep, often precipitous, and descend to the beds of the present creeks. There are numerous sharp bends in the courses of the streams of today, together with abandoned gateways and channels. There is, moreover, a significant defiance of structure in some places, while near by a high degree of adjustment has been attained.

The problem may, then, be stated interrogatively thus: What was the character and direction of the drainage that deposited the gravels? What changes have since taken place? How and in what order did they occur?

Methods of Work.

For the solution of this problem the writer has had recourse to both field and laboratory methods. In the field the gravels were mapped; their altitudes were determined at numerous places by means of an aneroid barometer, and specimens of the pebbles were collected at representative localities. The slopes of the valley sides were studied and their relations shown by sketches. The elbows of capture were visited and an attempt was made to work out their history.

In the laboratory the specimens from the Black Hills, numbering

over two hundred, were examined and classified according to type, as, for example, Algonkian quartzite, Cambrian quartzite, and quartz porphyry. Representatives of each type were compared with trimmed and labelled specimens collected by Professor Jaggar and Mr. Boutwell in 1898–9. Possible sources of each type were thus determined. In a number of cases the identification of a pebble was difficult or uncertain because of weathering and discoloration. In a majority of instances, however, the pebbles were identified with a considerable degree of certainty. The sources thus found were entered upon the map (Plate 1) as green rectangles and were connected by green lines with the localities at which the respective pebbles were collected.[1] In this way several important facts were brought to light which will be discussed in a later section. A separate map (Plate 3) was also made on which were platted the altitudes of the different portions of the gravels.

No such maps were constructed for the Bighorn region, since, for reasons that will appear later, no attempt was made to follow out the courses of the streams that deposited the gravels.

The Black Hills District.

The Gravels. *Character and Distribution.* At many places in the Black Hills, both within and without the region under discussion (Figure 1), occur patches of gravel and boulders, sometimes a hundred feet or more in thickness. The pebbles consist of well rounded fragments of quartz, schist, sedimentary rocks, and porphyries, which have an average size of one to three inches, while boulders six inches and even a foot in diameter are not uncommon. They occupy broad valleys, saddles on the divides, and patches on the shoulders of the valley sides far above the present streams. Their distribution in this region is indicated on the map (Plate 1). The main gravel body lies in Boulder Creek valley, where the gravels range in thickness from fifty to one hundred feet. In Boulder Park proper they are very thin and the underlying strata (Minnekahta limestone or Spearfish Red Beds) frequently appear at the surface. Indeed it may be questioned whether the deposits there found are of the same age as the main gravel body or only later, resorted gravel. From the comparatively uniform size and character of pebbles found in different parts of the

[1] The colors were not reproduced in the plate and for simplicity some of the lines were omitted.

Park the writer is inclined to the belief that they are thin residual patches of a larger mass that once covered that entire area. Southeast of Boulder Park are two patches of gravel that extend toward it, while farther to the southwest are gravel areas, mapped by Professor Jaggar, which lie on the general divide between Bear Butte and Park Creeks. Other patches mapped by him lie northwest of Deadwood and illustrate very well the characteristic habit of occurrence on the present stream divides. The arrangement of gravel areas, thus indicated, is suggestive of a former trunk stream, flowing east-northeast, with branches from the west and south.

The northward extension of the main gravel body makes a distinct inclination eastward at the head of Crook valley and reaches well up

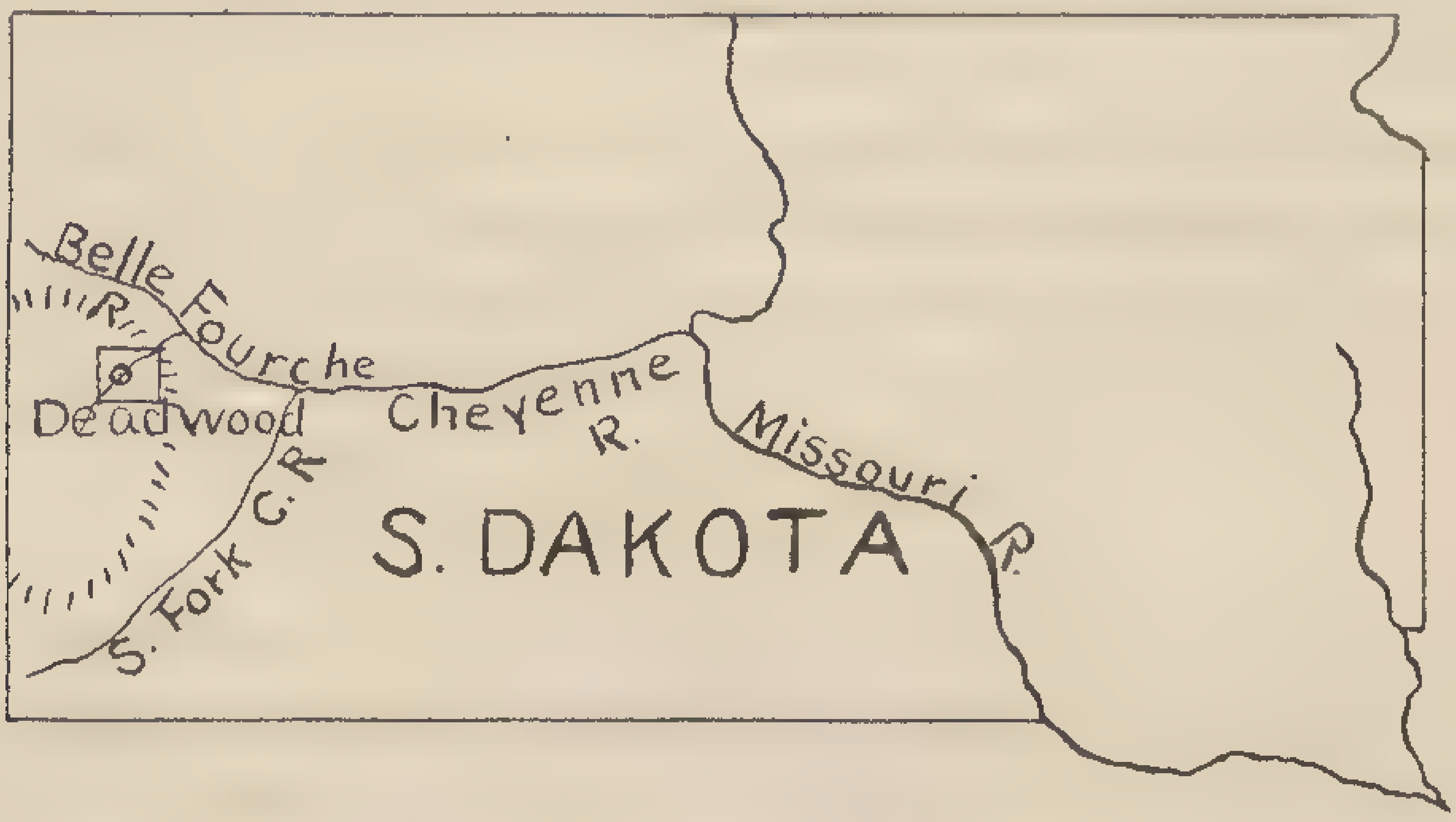

FIG. 1. Index map of Black Hills district.

on the flanks of the anticline, which forms its eastern side. Farther to the northwest there are two patches of gravel on the sides of Crook valley near its junction with Whitewood Creek, while other significant patches occur on the shoulders of Whitewood valley three miles west of Crook Mountain. These smaller gravel deposits, together with the eastward extension of the main body, already noted, have an important bearing on the story of capture, which forms so interesting a chapter in the drainage history of the region.

Sources. It will be seen from the map (Plate 1) that possible sources of all the types of pebbles found lie within the present drainage basins of Whitewood and Bear Butte Creeks. It is not necessary, therefore, to extend the limits of the ancient drainage area. The lines on the map that diverge from a numbered locality show the direction and range of sources from which its pebbles were derived. The data at

hand do not justify any quantitative statement as to the percentage of pebbles from any given source or direction, for it cannot be assumed that the collection with which comparison was made represents all the sources of a given type in this region. Nevertheless the divergence of the lines from every numbered locality toward the southwest is very striking and indicates that the ancient stream, which deposited the gravels, had its headwaters in the southwest, toward Terry Peak region and maintained a somewhat northeasterly course in much the same manner as do the present Whitewood and Bear Butte Creeks.

While the drainage basin and direction of discharge remain practically the same, the lines along which that discharge takes place are not identical with those of the ancient drainage. Bear Butte and Whitewood Creeks are now separate streams and the latter, instead of flowing through the broad ancient valley, occupied by the main gravel body, has been offset to a nearly parallel course about two miles northward. Some record of these changes is furnished by the gravels. At locality 16 (Plate 1), a little patch on a shoulder of Whitewood Creek three and a half miles below Deadwood, is found, in addition to the usual types of the main deposit, a peculiar spotted amphibolite, which has a possible source in the canyon of a small tributary of Whitewood Creek, about two miles south-southeast of Lead. At locality 9, farther down stream, all the characteristic types of locality 16 appear in the more recent alluvial deposits, and, in addition, a green porphyry similar to that described by Irving (p. 248) as quartz-aegirite porphyry. This does not occur at any of the other localities visited by the writer. The records of these two localities are successively more recent than that of Boulder Creek valley, since they represent successively deeper stages of incision of the headwaters of Whitewood Creek and its tributaries. Moreover their position with reference to the main gravel deposit and the course of the present stream is highly significant and gives strong evidence of capture and diversion first northward, then eastward.

Altitudes. In the process of mapping the gravels numerous measurements of altitude were made with an aneroid barometer. The corrected readings do not agree very closely with the elevations as given by the contour lines on the topographic map and have little absolute value. Nevertheless a comparison of the readings with each other is instructive, in that it brings out the direction of slope of the upper surface of the gravels and gives a basis for estimating that slope in feet per mile. It shows, also, the relation of the isolated patches, already mentioned, to the main gravel body. From the map (Plate

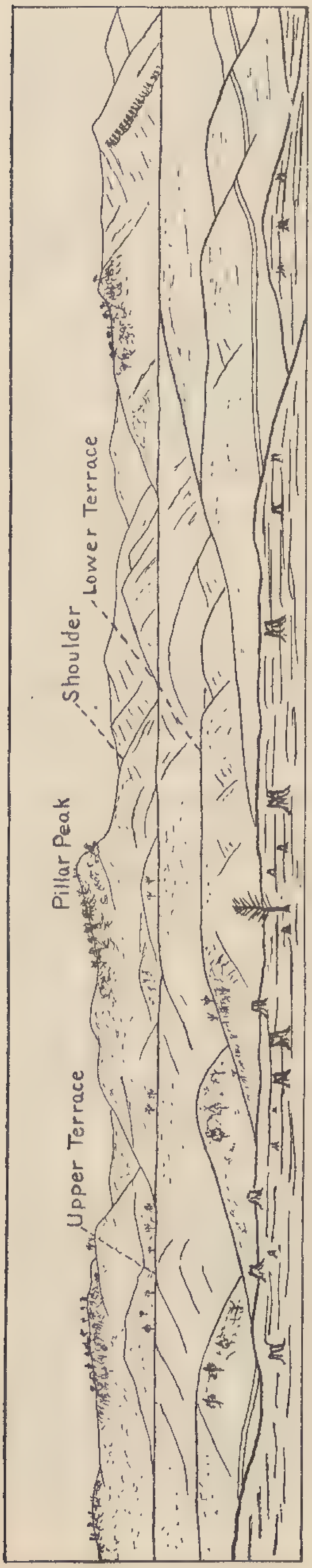

FIG. 2. Gravel terraces in Boulder Valley. Note the shoulder on the slope of Pillar Peak.

3) it will be seen that the surface of the latter slopes from an elevation of about 4,750 feet at the west to an elevation of about 4,350 feet at the northeast, seventy or eighty feet per mile. The altitudes thus add confirmatory evidence to that furnished by the distribution and sources of the gravels, with reference to the direction of the trunk stream. Moreover the altitudes of the two gravel patches southeast of Boulder Park, 4,425 and 4,450 feet respectively, are such as to favor the hypothesis of a tributary stream from the south.

The altitude of the gravel patches northeast of Crook Mountain, 4,290 feet, suggests that the main stream turned northward through the synclinal Crook Valley; but the eastward inclination of the main body at the head of the valley seems to indicate that the earlier course of the stream was directly east-northeast to the plains. These gravel patches may therefore represent a later diversion of the stream, by capture, through Crook valley.

The altitude of the gravels at locality 16 (Plate 1) is nearly three hundred feet lower than the surface of the main body at its western end. The slope between the two places is a little over one hundred feet per mile, a considerable steepening of the grade over that of the main body in its east-northeast direction. Here again the evidence confirms that already furnished by the distribution and sources of the gravels with reference to the capture and northward diversion of the main stream.

TERRACES AND SLOPES. In Boulder Creek valley two terrace levels may be

traced in the ancient gravels, the lower perhaps fifty feet below the higher. Both terraces may be clearly seen on the south side of the valley but the lower terrace is not so evident on the north side. The observer who stands on the north side of the valley, opposite Pillar Peak, may see the top line of the upper terrace stretching east and west, almost unbroken. The lower terrace level is less perfectly preserved but it may be traced along the hill-tops. The slopes ascending from the upper terrace are not very steep and break above into more gentle grades at a fairly well defined shoulder. The tributary streams, such as Two Bit and Pedee, have broad, V-shaped valleys that exhibit this feature very clearly. Above the higher, more gentle slopes occur residual knobs, such as the rocky summit of Pillar Peak. The ancient valley, of which the upper terrace formed the floor, is broadly open, has gentle slopes and relatively straight sides, features indicative of late maturity. This valley, however, has apparently been incised and opened in the floor of a still more ancient valley, for the shoulder, above indicated, points to more than one period of incision. The more gentle

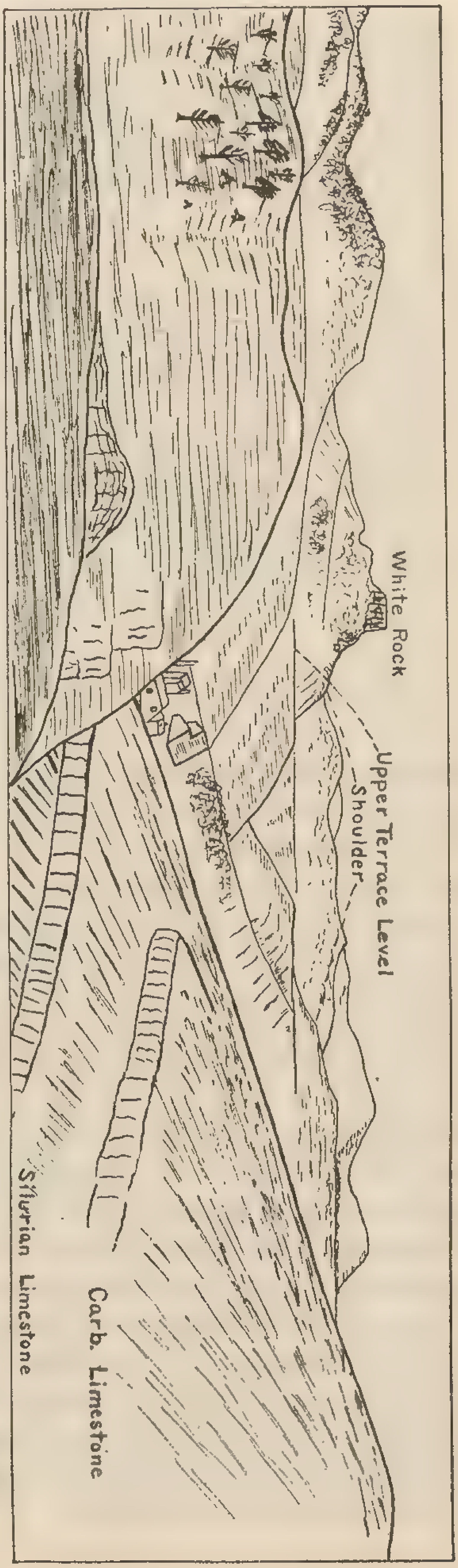

Fig. 3. Whitewood Creek, looking southwest from a point just below the west end of the gravel terrace.

slopes of the earlier valley show that it must have reached a more advanced stage of development before revival than the later one has since attained. The slopes produced by the dissection and penetration of the terraces by the present streams are steeper than those above noted. They bear every evidence of youth and represent a still

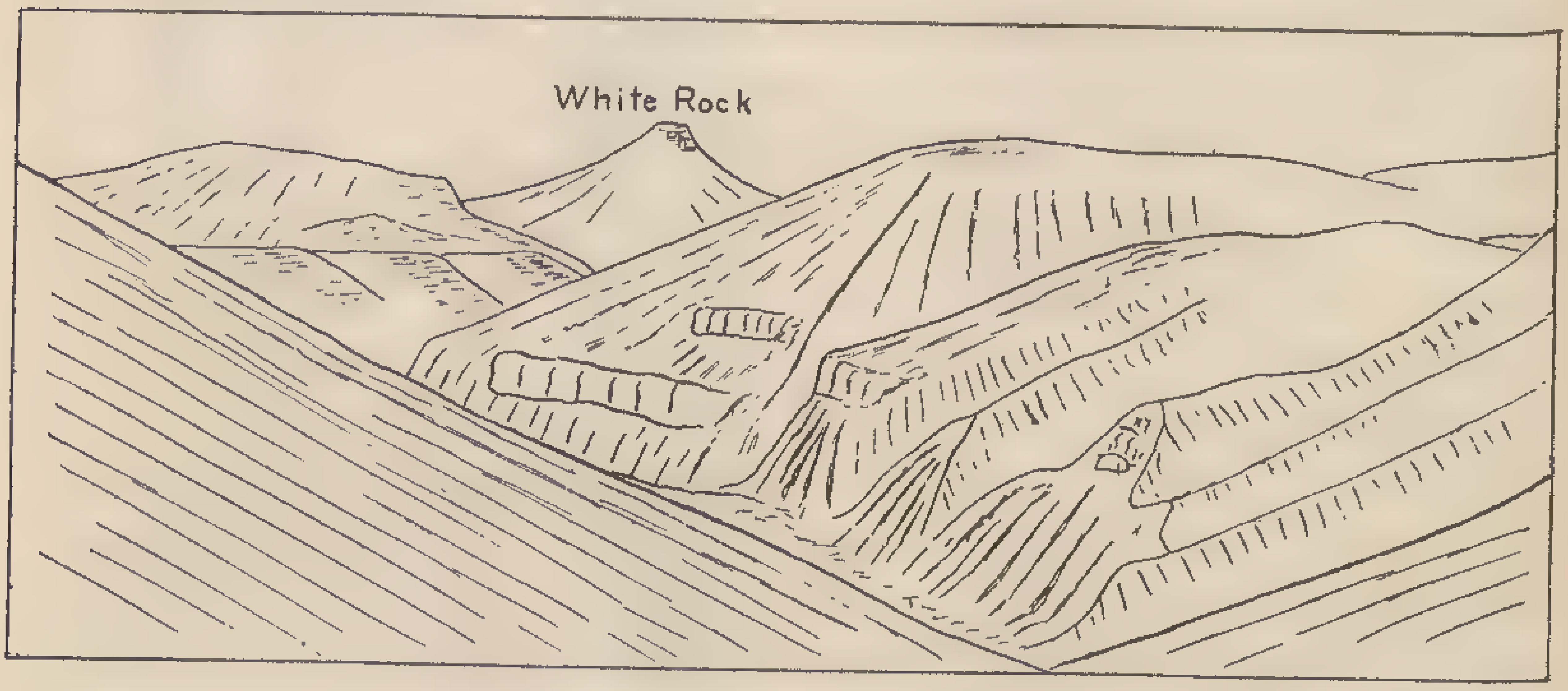

FIG. 4. Whitewood Creek looking southwest from a point half a mile below the west end of the gravel terrace.

more recent stage in the history of Boulder Creek valley. These features are illustrated in Figure 2.

In Whitewood Creek the lower terrace is not easily recognized but the upper terrace level may be seen extending southwest beyond Deadwood along the lower shoulders of the valley. Figure 3 represents the view in that direction from a point on the east side of Whitewood Creek just below the west end of the main gravel body. In it the terrace and the older valley sides, with the characteristic shoulder above, may be clearly seen. White Rock is a rather sharp-featured residual, but in the main the upper topography is subdued. Later incision has produced a steep-sided gorge, which is better shown in Figure 4, where the more gently sloping spurs of the older valley are truncated at about the terrace level. The latter may be traced down Whitewood Creek along the shoulders of the later gorge. On these shoulders lie the patch of gravel at locality 16 (Plate 1), already described, and a similar patch on the opposite side of the valley, mapped by H. G. Ferguson. The older Whitewood valley, in which the present gorge has been cut, was not so broadly opened as the ancient Boulder valley, and, since the rocks and structures in which both are cut are essentially the same, it may be inferred that less time was consumed in its excavation.

STREAM ELBOWS. *Bear Butte Creek —Boulder Park.* At the point where Bear Butte Creek enters Boulder Park it makes a rectangular bend northeastward, turning from a course across the strike of the rocks to one that follows the structure closely. The two patches of gravel just east of the bend have an elevation consistent with that of the main gravel body.

Boulder Park — Crook Valley. At the northern part of Boulder Park the main gravel body makes the eastward inclination already noted and points toward the wide gap in the outer hog-back ridge, now occupied by Spring Creek. The stream, which now drains Crook valley, is excavated in the weak strata of the Red Beds, which are here folded into a narrow syncline, and makes nearly a right angle with the direction just indicated. Moreover the gravel patches in Crook valley are fifty to one hundred feet lower than the elevation of the main body at the head of the valley. Here the evidence corroborates that already cited and points to the former continuation of the main stream through Spring Creek Gap and its later diversion northward through Crook valley.

Whitewood Creek. (*a*) The continuation of the high-level Whitewood valley beyond the west end of the gravel terrace has already been noted. The course of that valley makes a large angle with that of the ancient stream as shown by its gravel deposits.

(*b*). Three and a half miles below Deadwood, Whitewood Creek makes a rectangular turn eastward; but the high-level valley continues on for half a mile and ends at a saddle in the divide, which overlooks the Red valley and has been tunneled by the railroad in its escape from the gorge. The direction of the valley, however, is continued by an insignificant stream which drains into the Red valley. Just below the bend occur the two patches of gravel at locality 16 and across the canyon (Plate 1).

Sandy Creek. Sandy Creek joins Whitewood Creek at a rectangular bend a mile and a half west of Crook Mountain. The eastern limb of the bend continues the valley of Sandy Creek northwestward for nearly a mile. There the stream turns abruptly northeastward again; but a broad high-level wind gap occurs on the west side of the gorge, two hundred feet above the present creek, and beyond, in the same northwesterly direction, a small stream flows into the Red valley.

Spiegel's Gap. On the northwest flank of Crook Mountain there is a beautifully symmetrical V-shaped gateway, in the Minnekahta limestone, the arms of which rise in an escarpment four hundred feet above the level of Whitewood Creek. The stream that carved it un-

doubtedly had a radial course from off the mountain dome. Now the drainage through the gap is in the opposite direction. A little stream, working on the face of the escarpment, has appropriated the gap and has cut back sufficiently to divert the headwaters of a small stream in the Red valley and to lead them by a shorter course through the gap into Whitewood Creek, while the beheaded portion continues on its longer, gentler course outside the escarpment and joins the same stream two miles below.

Present Stream Courses. In Boulder valley the present stream courses bear little relation to the broad, ancient excavation, which they partly occupy. Insignificant streams flow both east and west from a divide established near the west end of the main gravel deposit. They are busily engaged in dissecting the terraces and entrenching themselves in the firmer rock beneath.

Elsewhere in the district the stream courses are in the main well adjusted to structures and notably follow the strike of the rocks. Whitewood and Bear Butte Creeks, the two master streams of the region, give clear evidence of superposition from superior strata since removed. Just below the town of Crook, Whitewood Creek cuts across a pinched anticline, not at its lowest point but nearly half a mile southeast of it, thereby severing the shoulder of the anticline from the main mass. Four miles farther southeast, Bear Butte Creek cuts through the same arch in a splendid gorge, five hundred feet deep, on the sides of which the anticlinal structure appears with almost the symmetry and beauty of a rainbow. None of the streams above noted have yet graded their valleys, though in some instances graded reaches have been established.

Summary of Field Evidence. An ancient stream, with possible tributaries from the west and south, flowed in a general east-northeast direction through Boulder valley with a slope of seventy or eighty feet per mile. Its sources were in the Terry Peak region and its drainage basin was probably equal to those of Whitewood and Bear Butte Creeks combined. There is good evidence that the predecessor of Bear Butte Creek joined the main stream, as a tributary, at Boulder Park and that it was later diverted northeastward by capture. If, however, such capture took place, it must have occurred previous to the conditions which permitted the incision of the present gorges; for Bear Butte Creek has been superposed on the anticline east of Boulder Park and now cuts through it in a fine gorge. The depth of the gorge, five hundred feet, is considerably greater than that of the later portion of Whitewood canyon, two hundred and fifty feet,

and there are no well defined shoulders on its sides. Probably the greater depth may be accounted for by the fact that Bear Butte Creek has a more direct course to its junction with Belle Fourche River and delivers its water at a lower level than is the case with Whitewood Creek.

The trunk stream probably had its original course directly outward through Spring Creek gap to the plains; but it was diverted northward at Boulder Park by a stream working in the soft strata of Crook valley. In this case, as in that of Bear Butte Creek, the capture must have taken place before conditions permitted incision; for the ancient stream, which would thus have become superposed on the anticline, did not have an opportunity to make any definite excavation in it. At this time the lower terrace in Boulder valley was cut to a level corresponding with the altitude of the gravels in Crook valley.

A second diversion northward occurred at the west end of Boulder valley, two miles below Deadwood. This time the stream was led on a somewhat steeper grade through the abandoned saddle, near locality 16, across or into the Red valley. Boulder valley was then permanently abandoned and its gravels formed a relatively broad and flat plain.

Meanwhile a stream, that had been working along the strike of the rocks north of Whitewood Peak, succeeded in undercutting and diverting a third time the main stream, which was then flowing northward. The sharp bend eastward near locality 16 was thus produced and Whitewood Creek probably then assumed the course it holds today. The history of the creek below this bend is, however, not simple. The stream that made the capture was not a single subsequent stream that by its own unaided endeavor succeeded in working back sufficiently to undercut the other. Probably it was composed of sections of at least two, and possibly several streams, whose northeast-flowing parts coalesced through successive captures. It seems certain that Spiegel's Gap was cut by a stream that flowed from off Crook Mountain dome and was diverted by a subsequent stream, working in the soft strata at the base of the escarpment. Likewise Sandy Creek, in its earlier history, probably flowed outward into the Red valley and was later diverted in a similar manner. There are also two or three streams from Whitewood Peak, whose subsequent branches may have taken part in the formation of the stream that made the capture, but their relations have not yet been worked out.

All of the captures described above appear to have taken place when

the streams were flowing at the level indicated by the shoulders along the top of the recent gorges. The fact that the result of the various captures has been to produce a master stream that flows northeastward, together with the fact that the master stream has been able to hold its own, in spite of superposition below Crook upon anticlinal structures, suggests that the conditions which permitted this piracy resulted from a tilting of the region toward the northeast.

A later uplift, or an acceleration of the earlier tilting, has caused the incision of the recent gorges and brought about the dissection and partial removal of the gravels. With the exception of the reversal of drainage at Spiegel's Gap, little change has been made in the adjustment already reached when the later movement began.

Discussion of the Literature. *Origin of the Gravels.* Newton and Jenney in their report (p. 44) recognize the Post-Tertiary age of the gravels. Darton in more recent investigations (a, p. 545) believes them to be of Pleistocene age, for he finds them in occupation of valleys cut in the White River deposits (Oligocene). Portions of the gravels he recognizes as being of stream origin; but he seems to think that those of the Red valley and outer portions of the hills are old lake deposits, for he speaks of the "old shore line" of the Pleistocene period as "carved mainly on the limestone slopes," while "to the eastward the earlier Pleistocene plain abuts against the slopes of the Lakota sandstone of the hog-back ridge, excepting where it extends out to the plains through wide, high gaps not now occupied by water courses." Crosby (p. 576) and Jaggar (a, p. 182) have also written with reference to the origin of the gravels. All the writers cited, except Crosby, express a belief in the stream origin of at least a portion of the gravels.

The latter argues that the gravels in question are the residual accumulations of thick layers of Tertiary sediments, from which the finer materials have been removed. Against this view the following facts may be advanced: (1) the distribution of the gravels is consistent with the arrangement of former drainage lines; (2) sections of the gravels often show them resting in stream-carved notches; (3) the slopes bordering the upper terrace level in Boulder valley appear to have the simple relation of valley side and aggraded floor; (4) certain patches of gravel, such as that of locality 16, are closely related to the upper valley slopes on which they lie; (5) if the gravels were residual accumulations, one might expect to find a larger percentage of cherty and concretionary forms than actually occurs.

Quaternary Lake (?). Jenney (p. 296) and later Darton (a, p.

545) speak of the outer gravel deposits as possibly of shore formation. The former (p. 298) thinks it "almost necessary to assume the occurrence of an extensive lake surrounding the Hills during the Quaternary period, when boulders resulting from erosion were transported by the agency of floating ice to the places where they now are found." Even granting the assumption that the boulders were transported by floating ice, it does not seem to the writer necessary to hypothecate a lake to float the ice blocks, since in the spring season of high water large streams would be able to transport ice cakes of considerable size great distances. So far as his observations have gone all the facts of distribution seem well explained by the hypothesis of stream washing. No wave-cut benches or cliffs were observed by the writer and none are definitely described by either Jenney or Darton. The deposits seem to have extended a considerable distance eastward and also southward and westward; for Darton finds them capping portions of the Big Bad Lands and also lying on slopes adjoining Cheyenne River and Beaver Creek valleys (a, p. 547). He refers to them, however, always as gravels and does not suggest any gradation, such as might be expected in lacustrine deposits of great extent, into finer and more uniform deposits (Davis b, p. 352). Moreover he does not delimit the lake in any way, except by the general reference to the Pleistocene shore-line already quoted.

Question of Uplift. According to Darton (a, p. 558) the Black Hills dome was uplifted and truncated in early Tertiary time so that the larger topographic features of the region were developed before the deposition of the White River beds. A good idea of the degree of truncation may be obtained by consulting his sections (a, p. 550; see also c, the Newcastle folio). He speaks of widespread planation of the Tertiary deposits during the early Pleistocene period, of the revival of old valleys and the rearrangement of drainage on the east side of the hills, due to an increased tilting to the northeast during the late Tertiary uplift. In evidence of this last he cites the offsetting of Pre-Oligocene valleys northward through canyons of Post-Oligocene age, while saddles mark the previous courses of the valleys. He further states that some of the offsetting in the present drainage has been largely increased by early Pleistocene erosion and recent stream robbing and that there appears to have been further uplift in late Pleistocene time, "for the present valleys below the level of the earlier Pleistocene high level deposits seem to be cut deeper than would result simply from the natural progression of a lower plane of base-levelling up the Missouri and Cheyenne Rivers."

On the other hand Johnson (p. 628–631) in a study of the Great Plains comes to the conclusion that both the construction and dissection of the heavy gravel deposits that constitute the upper members of the sedimentary series in those regions may be explained as the result of climatic oscillations without the aid of crustal movements. He argues that since the streams of the Great Plains have cut through the covering gravels to the old topography beneath and are there showing a tendency toward planation, the former inclination of the surface was not materially different from the present; or, if at all, it was probably greater because there is no indication that the earlier streams reached grade; hence it is unlikely that deformation could occur and yet permit the return of substantially the original conditions. He suggests a possible correlation of the changes in the Great Plains area with the different stages of the Quaternary Lakes of the Great Basin region and cites as evidence of the quiescence of Pleistocene times the general parallelism of the former lake shores.

The question is thus raised whether the modifications of Black Hills drainage and topography in Pleistocene and Post-Pleistocene times may not be explained as the result of climatic oscillation rather than of uplift. On the assumption of a constant base level changes of climate from less to greater relative humidity, and the reverse, would produce corresponding changes in the activity of streams, the former condition resulting in degradation, the latter in aggradation.

If, as Darton states, the larger topographic features of the region were developed in Pre-Oligocene time, it is probable that the broadly opened ancient valley of Boulder Creek was of Pre-Oligocene origin and that it was revived in the early Pleistocene period of erosion and aggraded to a level somewhat lower than the shoulder that marked the level at which Post-Oligocene incision began. Figures 2 and 3 represent the shoulders carved at this time on the slopes of Pillar Peak, White Rock, and other hills. This revival and subsequent aggradation may be explained by either of two hypotheses or by a combination of both: (1) uplift followed by subsidence; (2) climatic oscillation. In the absence of positive evidence of uplift or subsidence in connection with the revival and aggradation of Boulder valley and in the light of Johnson's work on the Great Plains and the work of Gilbert and Russell on the Great Basin area, it seems wiser to assign these early changes to climatic oscillations, since it is very generally believed that such oscillations occurred within the period to which these changes are referred.

The "offsetting of Pre-Oligocene valleys northward through canyons

of Post-Oligocene age" occurred after the completion of the aggradation stage, for the abandoned saddles and gravel patches are associated with the upper level of the gravel deposits. These changes could not therefore have been the result of late Tertiary uplift or tilting, as suggested by Darton. They were probably initiated by the conditions that produced the second period of incision. The "recent stream robbing" seems to the writer to be but the uniform continuation of the "offsetting" just discussed, for his observations show that all the larger captures at least, in the Boulder-Whitewood Creek region, took place before the later gorges were cut, and that the altitudes of the saddles and gravel patches are all related to the upper, more gentle slopes of the valley walls. The persistent offsetting of drainage, in such a manner as to develop northeast-flowing master streams is not satisfactorily explained by climatic oscillation alone and appears to indicate northeast tilting. It seems hardly probable that Whitewood Creek, for example, could retain its supremacy and trench the anticline on which it has been superposed, had not its direction coincided with that of tilting. That the tilting began rather slowly and was later accelerated seems to be indicated by the contrast in the slopes of the valley sides of earlier captor streams, such as the one which diverted Whitewood Creek from its Boulder valley course, and the streams of the present gorges. In the former case the valley sides are flaring, while in the latter incision has been so rapid that the slopes are generally precipitous.

The argument here set forth lends support to the view that Post-Oligocene incision began as the result of a gradual increase in relative humidity and that the later aggradation, by which the Pleistocene gravels were deposited, was occasioned by a return to more arid climatic conditions. Minor oscillations within each of these periods may have occurred but no evidence bearing on that side of the question is now at hand. In later Pleistocene times a gradual northeast tilting produced a second incision which was accompanied by extensive readjustments of drainage and was later accelerated so that steep-sided gorges were produced. This view does not appear to be inconsistent with Johnson's conclusions with regard to the Great Plains region, for it is entirely possible that differential uplifts in former areas of disturbance like the Black Hills and Bighorn Mountains might die out rapidly in the region of the Great Plains, in which case the ensuing destructive and constructive effects would die away also. Moreover the lake shores of the Great Basin, to which Johnson appeals in support of his theory of climatic oscillation without crustal move-

ment, have been shown by Gilbert (p. 366) to be no longer level. Some features noted in the Bighorn Mountains, which bear on the same point, will be discussed later.

In a recent paper Darton (d, p. 22) states that the river valleys of the Great Plains are now being built up rather than deepened.

Development of Drainage. Jaggar (a, p. 186) estimates the amount of Pre-Oligocene erosion at 6,000–8,000 feet. He thinks that during this process dome structures, which were not apparent at the initial surface, were gradually revealed and exercised an important influence upon the streams. After describing the drainage of several laccolithic domes he summarizes their erosion stages as follows (a, p. 276–7): "The cases cited show that laccolithic domes deflect regional master streams, and that subordinate drainage conforms strikingly to the relative resistance of rocks exposed. An early stage produces a dome-shaped hill with radial drainage. One radial stream gains advantage over its fellows and eats out the central portion of the dome to a soft stratum beneath. The outward dipping hard beds are undermined and drainage formerly radial outward becomes radial inward; a former mountain becomes a quaquaversal basin, inclosed by a horseshoe ridge. Recession of this ridge and continued erosion on the soft bed uncovers an arch of harder rock. Monoclinal shifting on the soft bed becomes easier than deep cutting into the dome, so the flanking beds are eroded down and a new radial drainage forms with two pronounced encircling streams. . . . The alternations from domical mountain to horseshoe-shaped ridge will continue under the erosive action of changing subordinate drainage until the porphyry is reached. Here monoclinal shifting is no longer possible, owing to lack of monoclinal structure."

In his discussion of Crook Mountain Jaggar (a, p. 272), expresses his strong inclination to the belief that Whitewood Creek was superposed upon the mountain from a position stratigraphically higher and unaffected by doming, and cites as evidence the apparent deflection of the stream from its course by the mountain. That monoclinal shifting of streams on the dome in question has had much to do with the present arrangement of drainage in that region the writer has little doubt. In fact it seems highly probable that Sandy Creek and the stream which now drains Crook valley originated as radial streams on Crook Mountain, before the Minnekahta limestone capping had been removed, and by shifting downward along the dip of the hard limestone rapidly cut their way in the soft Spearfish Red Beds. Probably, too, what may be called the lower Whitewood Creek and the

stream that carved Spiegel's Gap originated in a similar manner, cut through the hard Minnekahta limestone and excavated the weaker strata beneath. At this time there could have been no master stream flowing along the west flank of the dome, else Sandy Creek and the Spiegel's Gap creek would have joined it and would not have carved for themselves gateways outward to the Red valley. Field evidence suggests that this portion of Whitewood Creek has been formed by the coalescence of subsequent branches of several streams, through successive captures, and shows that the main stream has been diverted from a northerly course at the elbow three miles west of Crook Mountain. The present summit of the dome stands nearly five hundred feet above the level at which this capture occurred. At the time of the capture Crook Mountain must have already become a considerable eminence and superposition of Whitewood Creek upon it was therefore impossible. The apparent deflection of Whitewood Creek by Crook Mountain seems to the writer to be best explained as a response to structure by the development of a subsequent stream along the strike of weak beds. Where the strata bow outward around the mountain, there the stream following the strike bows outward also.

Conclusion. From a study of the field evidence and an investigation of the literature, the following drainage history may be outlined for the region under discussion. By the increase of relative humidity which accompanied the close of the Tertiary period, the Pre-Oligocene Boulder valley was revived, and, during the prolonged erosion of early Pleistocene times, it was broadly excavated. Later, by the return of more arid climatic conditions, it was aggraded to the level of the higher terrace. At that time its stream was probably joined by the predecessor of Bear Butte Creek and other tributaries and held its course east-northeast to the plains through the Spring Creek gap. At that time, too, Crook Mountain dome, already sufficiently uncovered to influence drainage, was sending radial streams in many directions. As a result of the northeast tilting, which followed the aggradation period, those streams which had northeasterly courses were given an advantage over their fellows and were allowed to cut more rapidly. Such a stream, working backward into Boulder Park, diverted the Bear Butte tributary. A similar stream, originally radial on Crook Mountain, found monoclinal shifting more easy than deep cutting. It accordingly shifted down the east flank of the dome and, by working rapidly headward through the soft Red Beds, diverted the main stream through Crook valley. The stream that made the next capture, two miles below Deadwood, was also favored by having

a northeasterly course. The third capture, west of Crook Mountain, was effected by a subsequent stream probably formed by the coalescence of several streams, which by monoclinal shifting had become annular with reference to Crook Mountain and the Whitewood Peak laccolith. The order of the steps in the development of this portion of Whitewood Creek has not been clearly determined; but the facts are probably these: lower Whitewood Creek, formerly radial but later becoming annular, diverted the waters of Spiegel's Gap Creek; the latter in similar fashion secured the Sandy Creek drainage, while Sandy Creek, with the probable assistance of subsequent drainage, developed with reference to Whitewood Peak, succeeded in capturing the main stream of the region.

The acceleration of the tilting in later Pleistocene to recent times has permitted the incision of the present gorges to the depth of over two hundred feet below the former valley floors and has caused the superposition of Bear Butte and Whitewood Creeks upon the anticline east of Crook Mountain. The gravels have been partially dissected and removed and the reversal of drainage through Spiegel's Gap has been accomplished by recent capture. The main drainage features, however, have been but slightly altered.

The Bighorn District.

The Gravels. The eastern flank of the Bighorn Mountains (Figure 5 and Plate 4), is cloaked with gravels similar in some of their aspects to those of the Black Hills. These deposits frequently rise on the backs of the upturned, crescentic masses of Carboniferous limestone toward rounded notches in the top of the ridge. Some parts of their slopes are rounded and are suggestive of flat, conical form; but in the main they make a fairly uniform cover of no great thickness, which descends from the lower flanks of the range toward the plains and conceals the bevelled edges of the upturned Per-

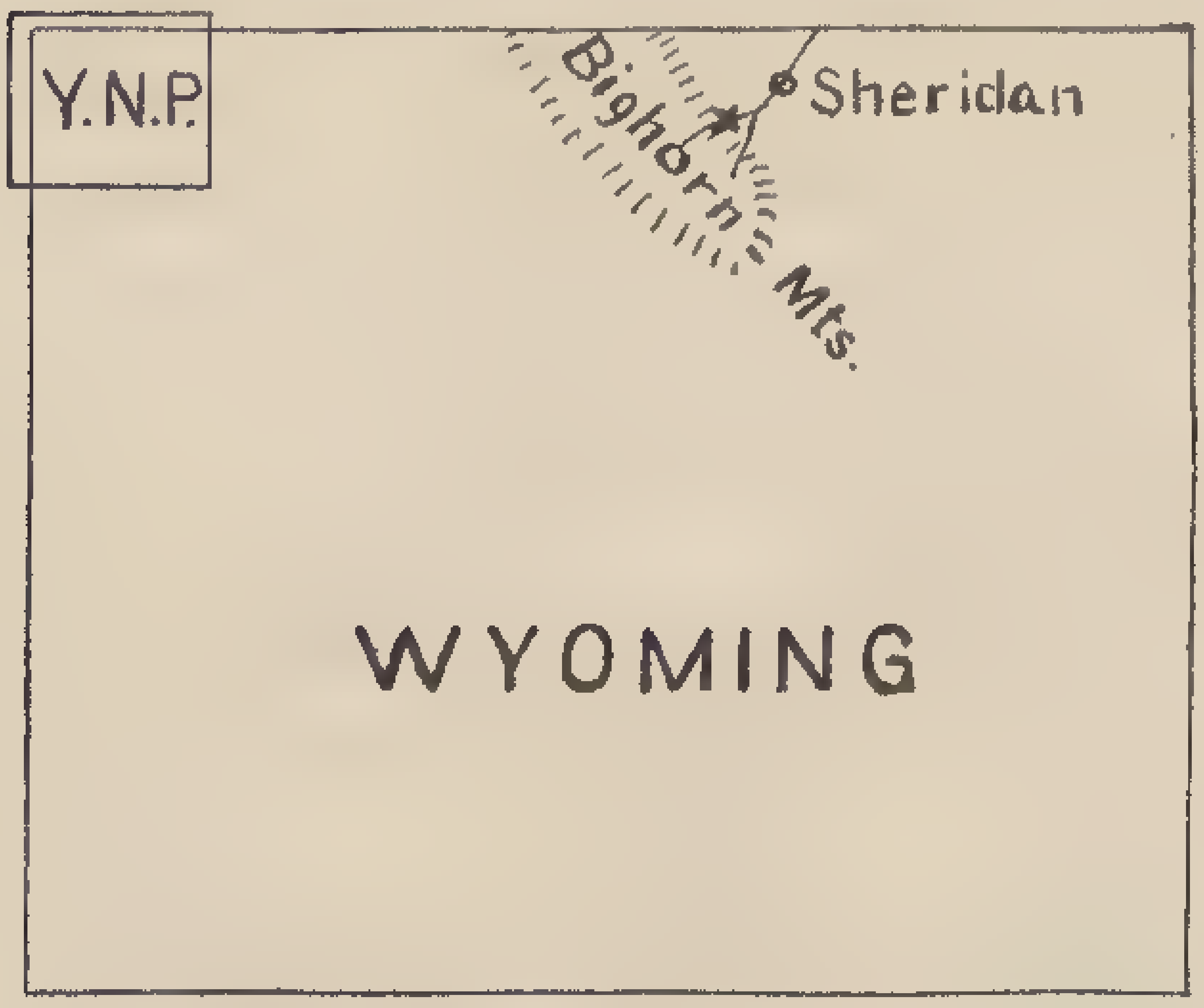

Fig. 5. Index map of the Bighorn district.

mian to Cretaceous strata, except where they have been exposed by later erosion. While these gravels cannot be traced along definite stream courses, as can those of the Black Hills, it is probable that they represent a former piedmont slope, formed by the union of contiguous, flat, alluvial cones, such as those described by Davis (b, p. 346). They have been deeply trenched by the present streams and numerous sections are thereby exhibited in which the unconformity of the gravels is clearly shown. The interstream uplands are smooth and regular and have a marked, but gentle slope of about five degrees in a direction slightly north of east. The gravels consist of rounded and subangular fragments of limestone, sandstone and chert, white quartz, Cambrian quartzite, and breccia, such as might easily have come from the strata now exposed along the top and flanks and in the canyons of the front rampart of the range. Although granite is abundantly exposed in the interior of the mountains at the present time and form steep walls for Big Goose Canyon only two miles from its mouth, granite pebbles in the gravels are rare or wanting, except that along the course of Big Goose Creek, stretching for perhaps one or two miles eastward from the mouth of the canyon, there are large, rounded granite boulders lying at the level of the gravel deposits, which are similar in many respects to those now found in the bed of the creek and were probably deposited by it when flowing at a higher level. The pebbles of the gravel have an average diameter of from one to three inches; but there are occasional boulders five inches to two feet in diameter. Although there are abundant evidences of glaciation in the interior of the range, ten to twenty miles back from the front rampart, such as moraines, scattered boulders, kettles, ponds and marshes, there is no definite evidence that the pebbles of the gravels in question are of glacial origin. Any scorings or polished surfaces that they may once have had, have been removed by weathering and only their subangular form is suggestive of glacial deposition. This, however, is not conclusive, since torrent pebbles, if not carried far, would not have time to become entirely rounded. The gravels were not found in contact with Tertiary deposits; but they overlie unconformably strata as high in the stratigraphic column as the Laramie. From their position and character, somewhat analogous to the like features of the Black Hills gravels, they may be tentatively assigned to the Pleistocene.

LITERATURE. The literature of the Bighorn region is not extensive. The earlier surveys of the western states and territories gave these mountains hardly more than a passing notice. G. H. Eldridge con-

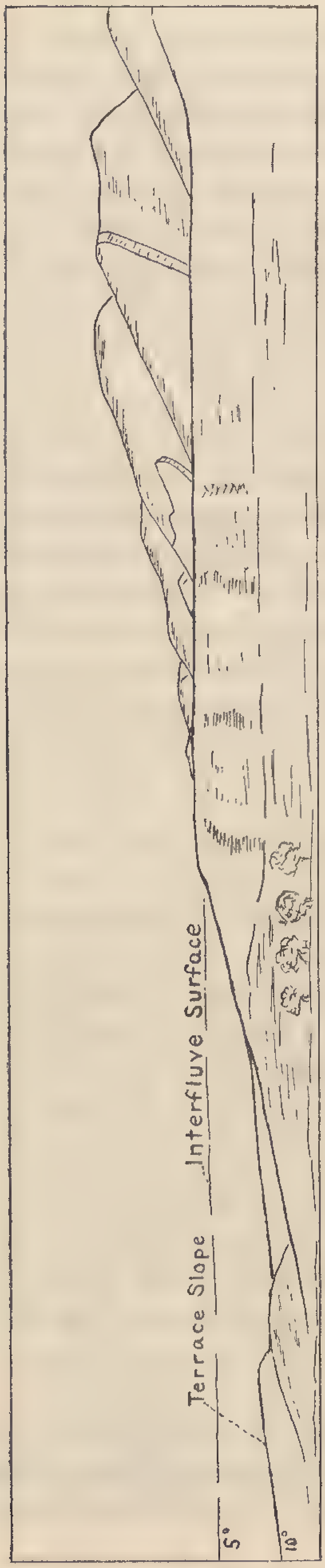

FIG. 6. Terrace slopes on the south side of Rapid Creek where it emerges from the Bighorn Mts.

ducted a reconnoissance in northwest Wyoming a few years ago and later papers have been published by F. E. Matthes, R. D. Salisbury and E. Blackwelder, and N. H. Darton (b and d). Other scattering references were found, which are not available at the time of the present writing. Scant account is given of the gravels in question; for these papers are devoted chiefly to the discussion of other problems. Where the gravels are mentioned, they are referred to the Quaternary period.

SLOPES. The interfluve[1] surfaces of the gravel deposits appear to be closely related to the somewhat gentler slopes of the upper portions of the front rampart, as though, in a previous period of erosion, the mountains had been reduced to a lower relief than that of the present and the cloaking gravels had been spread along their flanks at a faint angle. Now both mountain slopes and gravels have been deeply incised and shoulders, more or less well defined, on the sides of the gateways by which the streams emerge from the mountains, mark the level at which the later cutting began. Successive stages in the down-cutting are registered in the terraces cut in the gravels and the underlying rock. The down-valley slopes of the terrace plains are steeper than those of the interfluve surfaces. On the south side of Rapid Creek (Plate 4), a comparison of the interfluve slope with that of a well-marked terrace plain below showed the angle of the former to be five degrees while that of the latter is ten degrees (Figure 6).

[1] A term used by Professor Davis to indicate the uncut portion of a slope between two consequent streams.

QUESTION OF UPLIFT. As in the case of the Black Hills, the early erosion of the Bighorn Mountains, the accumulation of the gravels and the subsequent incision of both may be explained by either of the hypotheses of crustal movement or climatic oscillation. As regards the earlier erosion history, the writer has collected no data in favor of either hypothesis; but he has found some evidence which seems to indicate uplift, in some form, as a cause of the later incision; and that is the relation of the angles of interfluve surface and terrace plain slope above mentioned.

Climatic Oscillation. If we consider the hypothesis of climatic oscillation we must assume a constant base level. Under such conditions, any increase in the cutting power of the stream, permitted by an increase in the relative humidity of the region, would tend to lower the grade and make the angle of slope of the terrace plains AC and AD (Figure 7, I) less than that of the interfluve surface AB. If now more arid climatic conditions should return and cause the streams to cease degrading and to begin instead a process of aggradation, the ensuing changes in the slopes of the terrace plains would be simply the reverse of those already indicated and in no case would the slope of a lower terrace plain be steeper than that of its neighbor above. It seems evident therefore that climatic oscillation cannot be regarded as the only cause of the incision noted.

Crustal Movement. The hypothesis of crustal movement may be considered under the several heads of simple uplift, tilting, and warping. If the region were to undergo simple uplift as a rigid body the result would be to lower the base level AE to the position GH (Figure 7, II) without altering the angle of inclination of the interfluve surface AB. Assuming the process of uplift to be sufficiently slow to permit the grading process practically to keep pace with it, so that we need not consider the retreat of a waterfall in our section, we should find that all the terrace plains, such as GC, formed in the down cutting, would be steeper than the interfluve surface AB. As uplift slackened and ceased, if other conditions remained unchanged, the later terrace plains would gradually become parallel with the interfluve surface AB, as in GF. This supposition accounts for all the observed facts.

If the region were tilted on an axis shown in section at F (Figure 7, III) in such a manner as to make the line AE, which formerly coincided with base level, take the position GH, the interfluve surface AB would take the less inclined position GC. In order to maintain the grade AB, which the uniformity of other conditions here assumed would necessitate, the portion of the stream course below the point

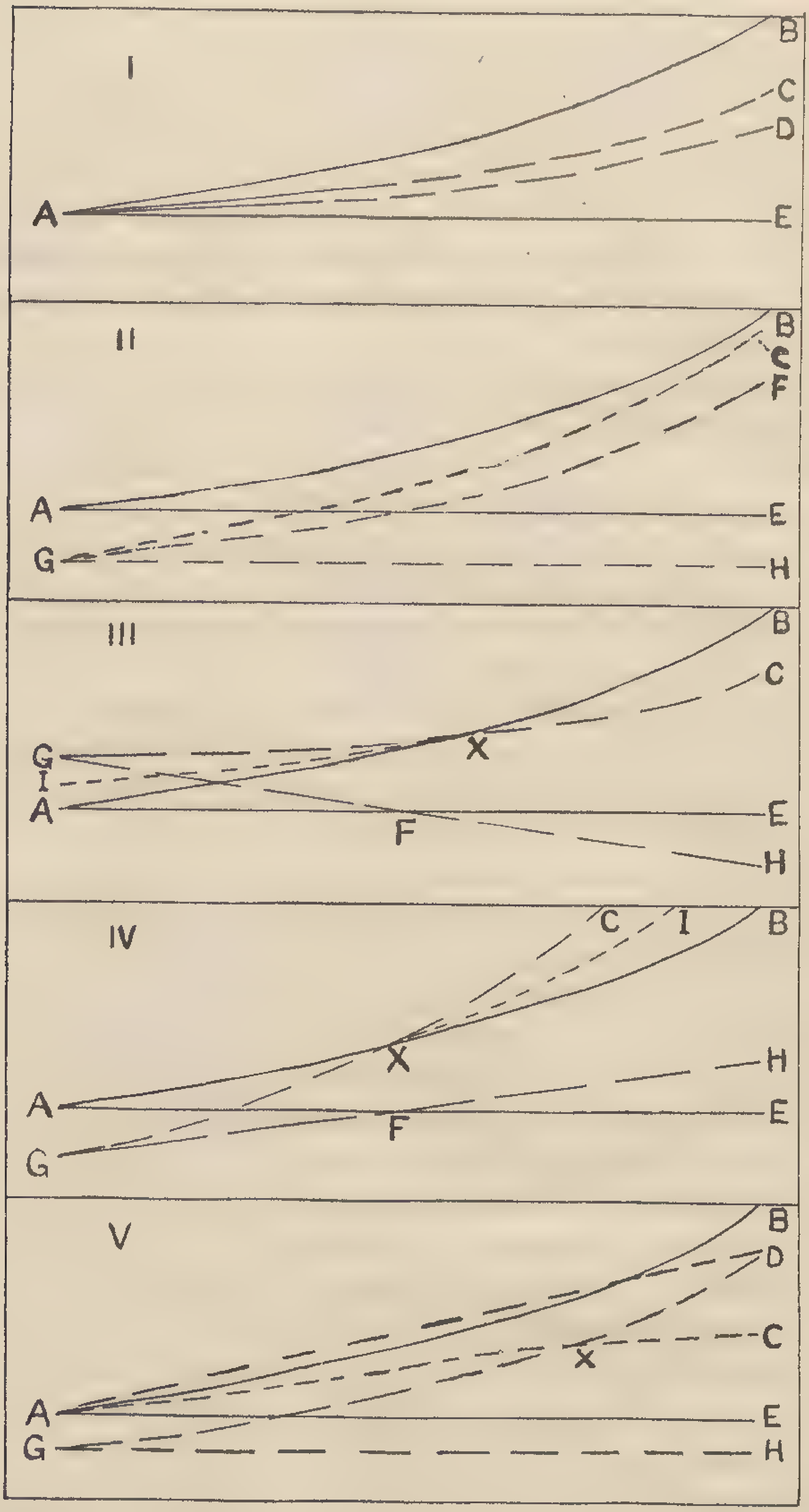

FIG. 7. Diagram to illustrate hypotheses of climatic oscillation and crustal movement.

X would be degraded while that above X would be aggraded. In that part of the valley side included in the angle GXA, any terrace plain, IX, would have a steeper slope than the interfluve surface GX, while above the point X the former surface XC would be cloaked with new gravels and no terraces would be distinguishable. In the region under discussion there was no tendency toward aggradation. On the contrary the streams at all the places noted, even well up toward their sources, were uniformly degrading. If aggradation was taking place anywhere, it was in lower courses of the streams remote from the locality studied.

If tilting in the reverse direction had occurred (Figure 7, IV), under the uniform conditions here postulated, the portions of the stream courses above X would be degraded while those below would be aggraded and any terrace plain XI in the degraded portion CXB would have less inclination than the interfluve surface XC. Here again the conclusion is contrary to the observed fact.

If the region were warped the base level would be raised or lowered according to whether the general effect on the region in question was one of depression or elevation. In the former case, other conditions remaining the same, the streams would aggrade their valleys; in the latter, the base level AE (Figure 7, V) would be lowered, as in GH. If the warping were broad enough to permit all parts of the surface in the region under discussion to be raised above its former grade, now represented by GD, as in AD, the effect would be similar to that already outlined for the case of simple uplift and would agree with the observed facts. Degradation would occur all along the line until the grade GD was attained and terrace slopes formed in the down cutting would be steeper than the interfluve surface. If, however, the warping were more local, so that part of the region were sunk below its former grade while other parts were raised above it, as in AC, the portion AX so raised would be degraded while the other portion XC would be aggraded. The effect would be similar to that of tilting as above noted and would not agree with the observed facts.

From this discussion it seems clear that climatic oscillation, the occurrence of which is not denied, is not alone sufficient to account for the phenomena noted; but that simple uplift, or broad upward warping, was an important cause of the down cutting.

Drainage Changes. As a result of this incision various changes in drainage have been inaugurated in the region and may be seen in active progress. The upturned members of the Permian to Cretaceous strata are but poorly protected by the overlying gravels. Subsequent streams are accordingly being developed along the strike of the weaker

beds. Streams flowing consequent upon the initial slopes of the gravels have been and are being beheaded and diverted by the active subsequents, while newly formed tributaries, flowing down the steep, infacing slope of the upturned, eastward-dipping beds, are following a course directly opposite to that of the initially consequent streams. Such streams have been termed "obsequent" by Davis (a, p. 134). The retreat of what may be called the obsequent slope is uncovering lower beds on which new streams are forming, tributary to the sub-

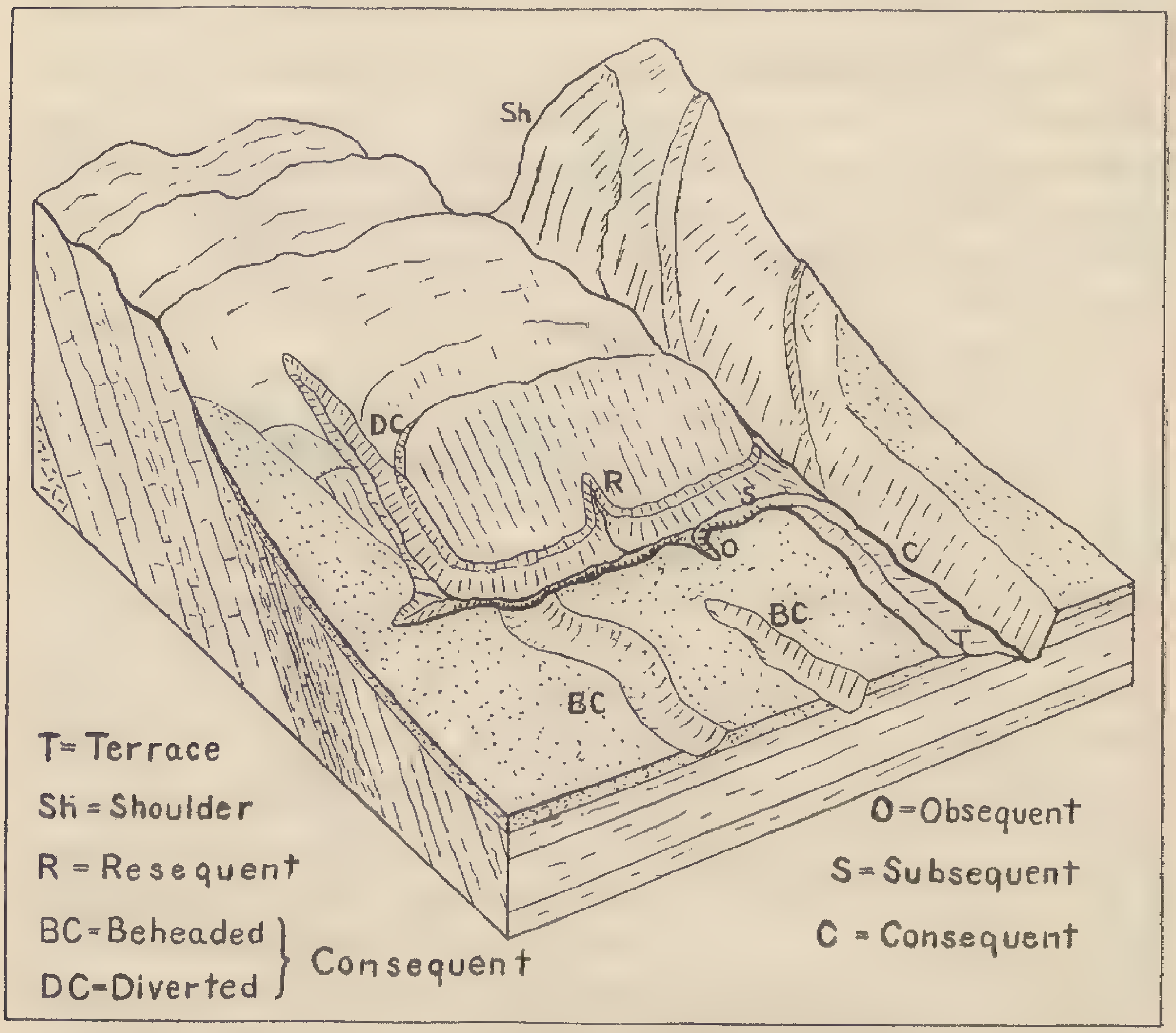

Fig. 8. Diagram to illustrate drainage relations in the Bighorn district.

sequents and having a consequent direction, though in this case that direction has been resumed after an interval in which that portion of the slope has been occupied by obsequent drainage. Such streams have been named by the same writer (c, p. 629) "reconsequent" or "resequent." Examples of some or all of these types of streams are to be found at various places along the east flank of the mountains.

Big Goose Creek. A particularly fine locality (diagrammatically

represented in Figure 8), where all are shown, occurs at the mouth of Big Goose Canyon (Plate 4). Big Goose Creek, the master consequent stream, has carved its V-shaped gateway nearly one thousand feet below the shoulder, which marks the junction of the newer and older slopes on its valley side (Figure 9) and still rushes, as a foaming torrent, over an uneven and bouldery bed. The opportunity thus given for the development of drainage, adjusted to structure, is great.

The Red Canyon. A subsequent tributary enters the creek from the south just after its emergence from the front rampart. This tributary, by gnawing headward for a mile and a half along the strike of the rocks, has carved for itself in the soft red beds of the Chugwater formation (Darton b, p. 397) a deep canyon. The rich, red

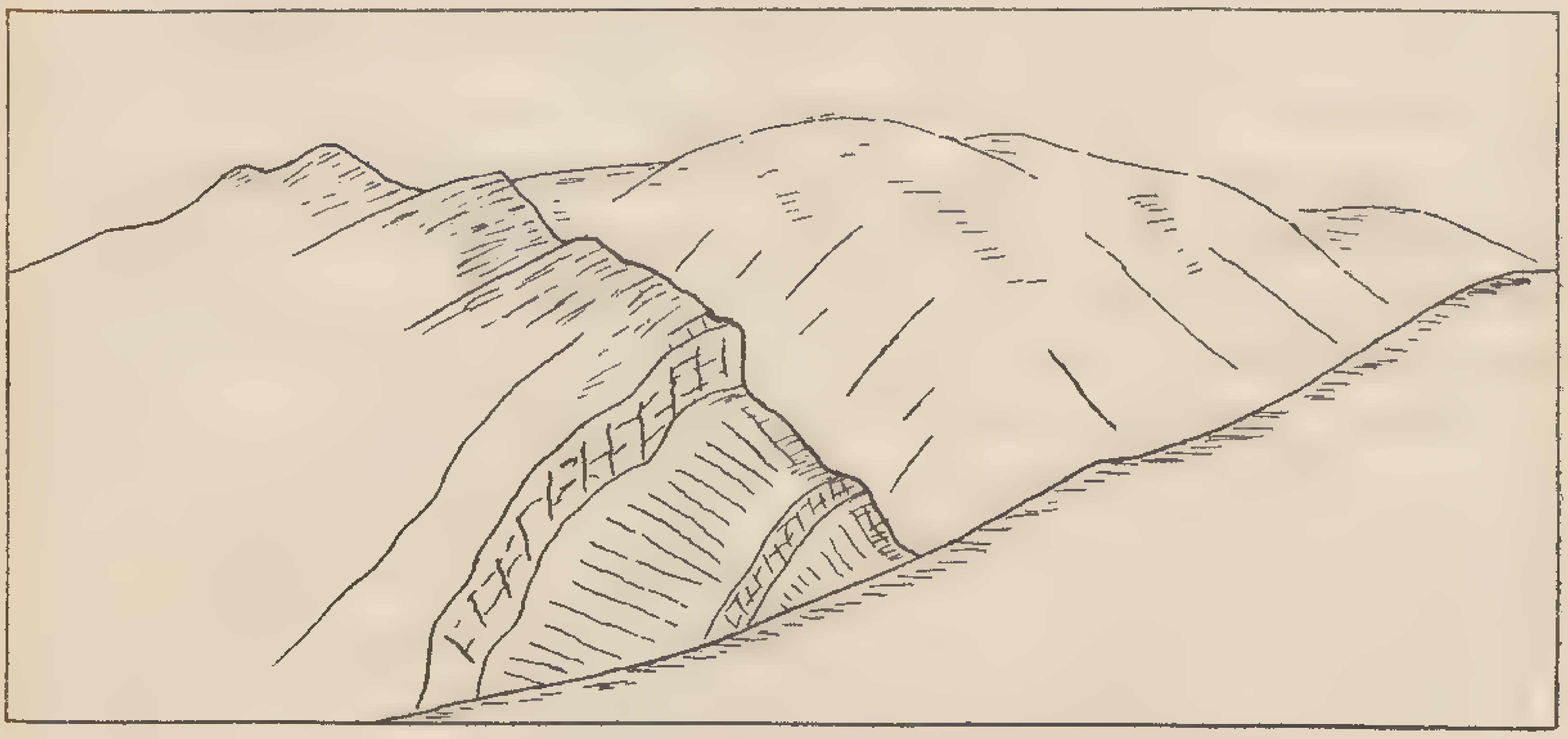

FIG. 9. The gateway of Big Goose Creek from the north.

color of the sandstones and shales, interrupted by white streaks, caused by lenses of gypsum, and by a narrow purplish band, due to the presence of a thin bedded, fine textured limestone near the bottom of the series, is displayed continuously on the east side of the canyon, where the wall in many places is almost sheer in its descent, and lends to the canyon an appearance of striking beauty. On account of the strong monoclinal dip of the strata eastward, there has been monoclinal shifting, concomitant with incision. The shifting began and continued for some time along the dip of the thin bedded limestone just mentioned; but the limestone has finally been cut through and the stream is now working on the weaker red sandstones beneath it. The result of the shifting has been to produce on the east side a steep and, in places, precipitous wall, while on the west side the slope, stripped

of soft beds, coincides with the dip of the limestone, except near the bottom, where the latter has been removed and the slope is steeper. The subsequent stream in the Red Canyon is working actively, during the moister seasons, on a slope of about seven hundred feet to the mile and is reaching headward toward Diamond Creek, its next consequent neighbor to the southeast. The uncut strip between the two streams is scarcely more than a quarter of a mile wide and the decapitation of Diamond Creek may be said, geographically speaking, to be imminent.

Beheaded Streams. The threatened fate of Diamond Creek has already overtaken an unnamed, minor consequent, which joins Big Goose Creek about two miles and a half below the Red Canyon. The diverted portion of the beheaded stream, which cuts rather sharply into the mountain side, because of the steeper slope and shorter course permitted by the capture, joins the subsequent at nearly a right angle and forms, according to the map, the headwaters of that stream; but in the field the canyon is seen to be continuing its headward growth along the strike of the rocks, ready for further piracy. On the eastern rim of the canyon, opposite the elbow of capture, is a well preserved rounded notch that gives a sharply defined cross section of the former consequent valley, which may be clearly seen, following a somewhat irregular course down the slope eastward. This valley was cut by an insignificant stream that did not incise its channel deeply; but it is worthy of description as a fine example of the class of beheaded consequent streams, for it is engraved upon the slope with diagrammatic clearness. Other minor consequent gulches, originating farther down the slope, would not at first sight be considered as members of the class just mentioned; but since ground water, which might otherwise contribute to their maintenance, is intercepted by the subsequent; and since, on account of the presence of the subsequent, they are forever debarred from extending their headwaters beyond it into the upper portions of their rightful drainage basins, they are as truly beheaded, in the sense of having lost part of their drainage area, as are those streams where actual capture has occurred.

Obsequent Gashes. Within the red canyon obsequent gashes occur here and there on the east wall. In only one case observed by the writer had the cutting progressed sufficiently to develop even a puny trickling stream. The immaturity of the subsequent, which is still engaged in down cutting and monoclinal shifting, is doubtless responsible for the present embryonic condition of the obsequent drainage. It is probable, too, that on account of the strong eastward dip of the

strata the retreat of the cuesta-like wall, by monoclinal shifting, has been able all along its length very nearly to keep pace with the tendency to develop obsequent drainage. The limit of shifting will be reached when grade is attained by the subsequent streams; and from that time on the retreat of the wall will be slower, because it will then depend only upon the slow process of weathering and the chance undercutting of the stream. The obsequents, on the other hand, will continue to work vigorously, so that their influence upon the drainage and topography will become more and more apparent until that time when all the activities of the region decline toward old age.

A Resequent Rill. On the western wall of the Red Canyon wet weather drainage flowing down the uncovered slope of the purple limestone, has gashed it near the bottom and the gully thus produced is growing headward by sapping. Already the incision has reached the water table and a permanent rill fed by springs has been established. The direction in which this rill now flows is identical with that which a consequent stream would have. The rill, however, cannot be termed consequent because during the removal of superior strata the surface on which it flows has been produced by the retreat of an obsequent slope and the present direction of flow has been, as it were, resumed after an interval in which the opposite direction obtained. It belongs therefore to the class of resequent streams, of which there are other examples in Pennsylvania, the Jura Mountains, and elsewhere. The radial streams on Crook Mountain and other domes in the Black Hills are probably also members of this class; for the slopes on which they run are certainly not the original surfaces of the domes and, in the development of the present surfaces by the removal of superior strata, several generations of obsequent slopes may have successively retreated along the dip of the beds, each retreat being followed by the development of resequent drainage until the present status was reached.

Summary.

In the Bighorn Mountains, as in the Black Hills, the Pleistocene period seems to have been marked by extensive denudation and the accumulation of gravel deposits. Since the deposition of the latter, Big Goose Creek and other streams have been permitted to entrench themselves deeply below their former valley floors. That this incision is due to uplift or broad up-warping rather than to climatic oscillation

alone is shown by the relation of the terraces formed during successive stages of down-cutting. Great opportunity has thus been given for the development of adjusted drainage. Fine examples of master consequent, subsequent, and beheaded consequent streams are shown, while less perfectly developed specimens of obsequent and resequent streams are also to be found. The general immaturity of all the streams described indicates that the uplift which permitted their development was relatively recent and may even be still in progress.

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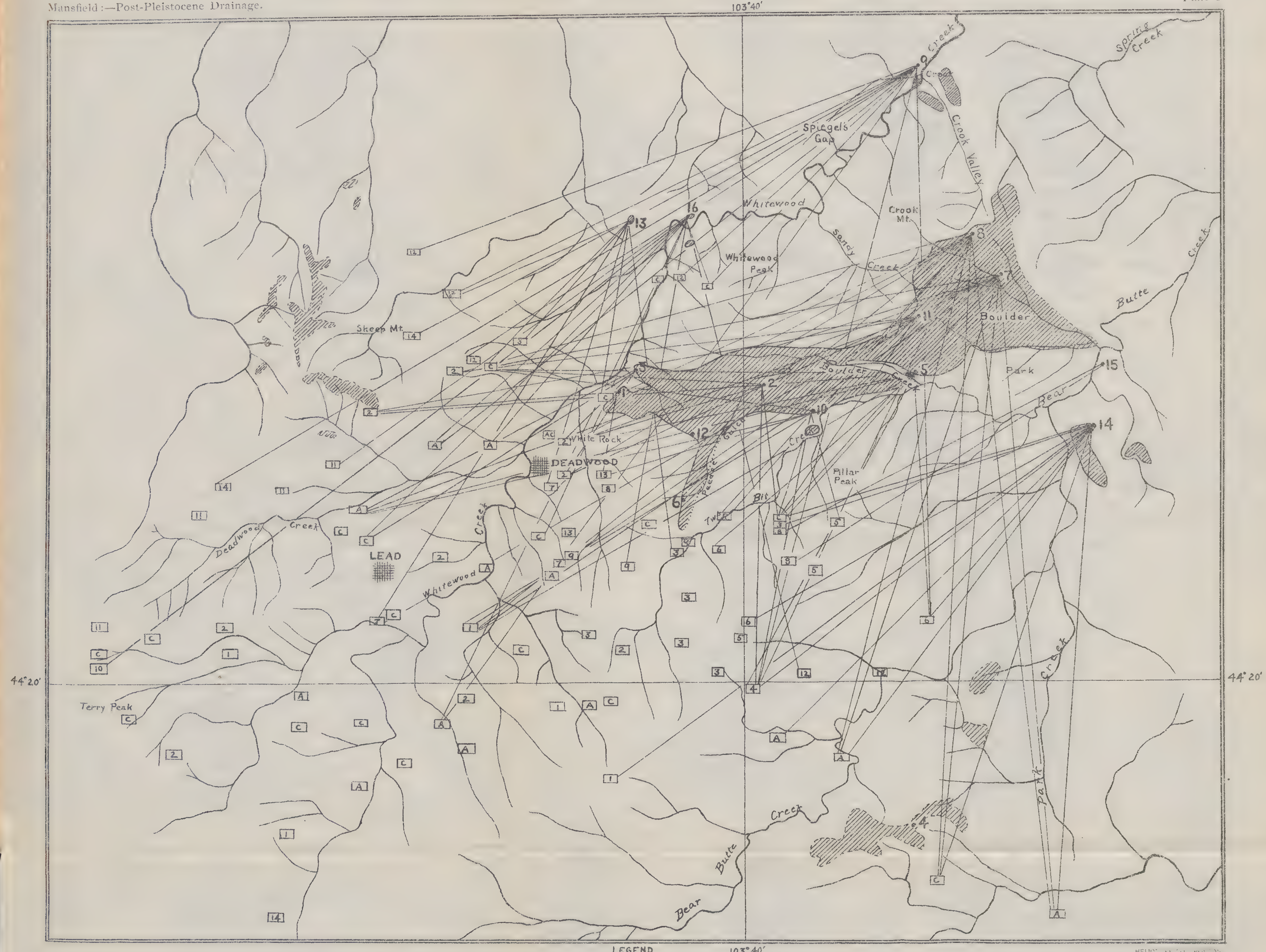
EXPLANATION OF PLATES.

Plate 1. Map of the Black Hills area showing present distribution of gravels, possible sources of pebbles, and possible routes of pebbles from sources to localities where found.

Plate 2. Topographic map of the Black Hills area.

Plate 3. Map showing altitudes indicated by aneroid barometer.

Plate 4. Topographic map of the Bighorn area. The Red Canyon joins Big Goose Creek from the south near the center of the map.



LEGEND

Pleistocene Gravels
Rectangles = Possible Sources of Pebbles

—— Observed general boundaries
.... Inferred general boundaries
– – – Mapped by T. A. Jaggar Jr

Letters (16 etc.) = localities from which pebbles were collected
A = Algonkian C = Cambrian 1-14 = Porphyries

Lines connect possible sources with localities from which pebbles were taken.

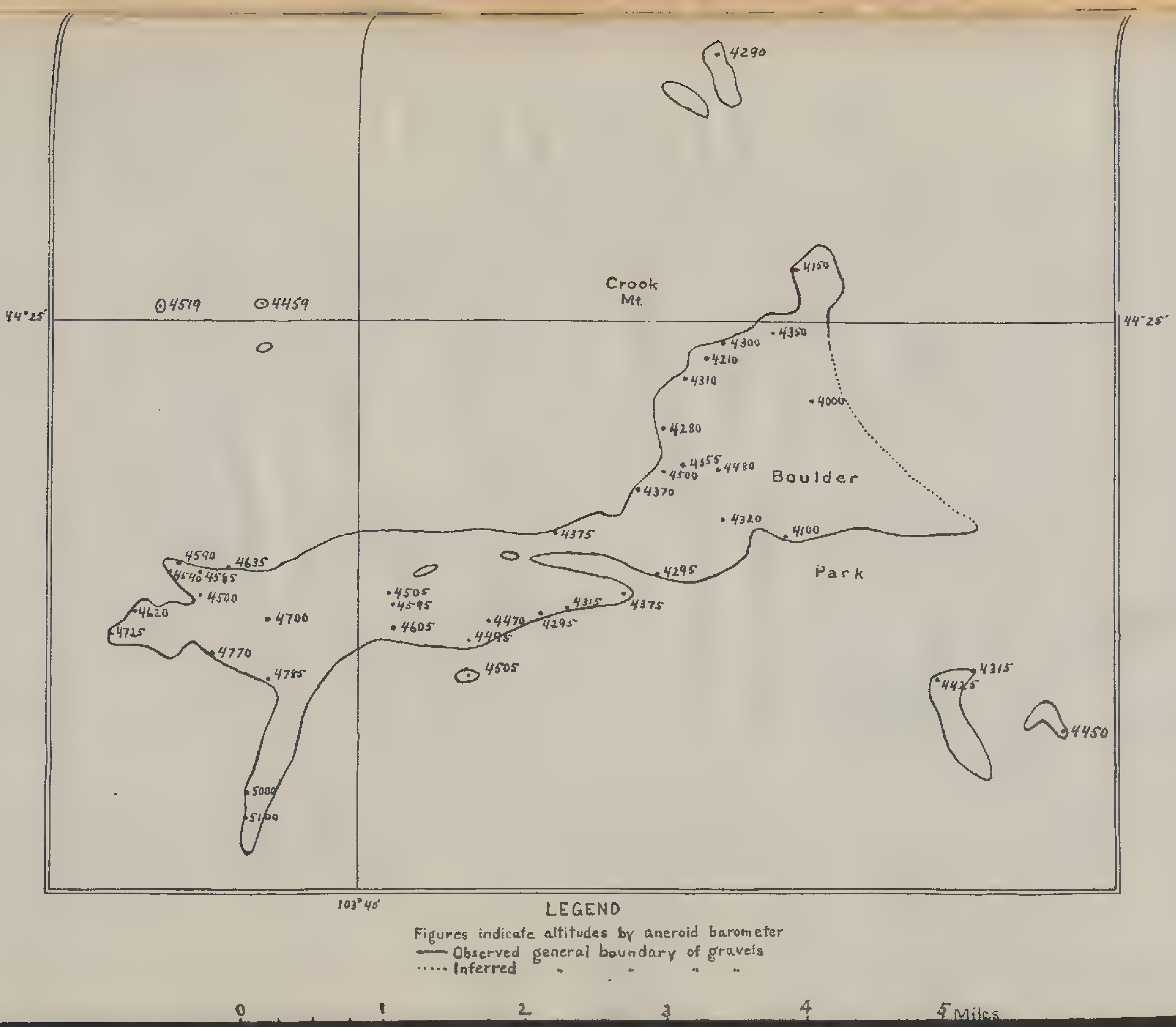
Drainage and Culture from Spearfish and Sturgis Sheets U.S.G.S.

0 ½ 1 2 3 4 5 Miles

HELIOTYPE CO., BOSTON.

PORTIONS OF THE SPEARFISH AND STURGIS S. D. QUADRANGLES.

Contour interval 50 feet.
Datum is mean sea level.


4290
Crook Mt.
4519
4459
44°25'
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4350
4300
4210
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4000
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Boulder
4370
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Park
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4590
4635
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4725
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4375
4770
4785
4505
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4425
4450
5000
5100
103°40'
LEGEND
Figures indicate altitudes by aneroid barometer
Observed general boundary of gravels
Inferred " " " "
0
1
2
3
4
5 Miles

HELIOTYPE CO., BOSTON

PART OF THE DAYTON WYOMING QUADRANGLE.

Scale $\frac{1}{125000}$

1 ½ 0 1 2 3 4 5 Miles

1 ½ 0 1 2 3 4 5 Kilometers

Contour interval 100 feet.

Datum is mean sea level.

The following Publications of the Museum of Comparative Zoölogy are in preparation: —

Reports on the Results of Dredging Operations in 1877, 1878, 1879, and 1880, in charge of ALEXANDER AGASSIZ, by the U. S. Coast Survey Steamer "Blake," as follows: —

H. AUGENER. The Annelids of the "Blake."
C. HARTLAUB. The Comatulae of the "Blake," with 15 Plates.
H. LUDWIG. The Genus Pentacrinus.
A. MILNE EDWARDS and E. L. BOUVIER. The Crustacea of the "Blake."
A. E. VERRILL. The Alcyonaria of the "Blake."

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of ALEXANDER AGASSIZ, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

LOUIS CABOT. Immature State of the Odonata, Part IV.
E. L. MARK. Studies on Lepidosteus, continued.
" On Arachnactis.
R. T. HILL. On the Geology of the Windward Islands.
W. McM. WOODWORTH. On the Bololo or Palolo of Fiji and Samoa.
AGASSIZ and WHITMAN. Pelagic Fishes. Part II., with 14 Plates.

Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieutenant Commander Z. L. TANNER, U. S. N., Commanding, in charge of ALEXANDER AGASSIZ, as follows: —

A. AGASSIZ. The Pelagic Fauna.
" The Panamic Deep-Sea Fauna.
H. B. BIGELOW. The Siphonophores.
K. BRANDT. The Sagittae.
" The Thalassicolae.
W. R. COE. The Nemerteans.
W. H. DALL. The Mollusks.
REINHARD DOHRN. The Eyes of Deep-Sea Crustacea.
H. J. HANSEN. The Cirripeds.
HAROLD HEATH. Solenogaster.
W. A. HERDMAN. The Ascidians.
S. J. HICKSON. The Antipathids.
J. P. McMURRICH. The Actinarians.
E. L. MARK. Branchiocerianthus.
JOHN MURRAY. The Bottom Specimens.
P. SCHIEMENZ. The Pteropods and Heteropods.
THEO. STUDER The Alcyonarians.
M. P. A. TRAUSTEDT. The Salpidae and Doliolidae.
H. B. WARD. The Sipunculids.
W. McM. WOODWORTH. The Annelids.

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AT HARVARD COLLEGE.

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The BULLETIN and MEMOIRS are devoted to the publication of original work by the Professors and Assistants of the Museum, of investigations carried on by students and others in the different Laboratories of Natural History, and of work by specialists based upon the Museum Collections and Explorations.

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Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieut. Commander Z. L. Tanner, U. S. N., Commanding, in charge of Alexander Agassiz.

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of Alexander Agassiz, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

Reports on the Scientific Results of the Expedition to the Eastern Pacific, in charge of Alexander Agassiz, on the U. S. Fish Commission Steamer "Albatross," from October, 1904, to April, 1905, Lieut. Commander L. M. Garrett, U. S. N., Commanding.

Contributions from the Zoölogical Laboratory, Professor E. L. Mark, Director.

Contributions from the Geological Laboratory, in charge of Professor N. S. Shaler.

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Nov. 23, 1906

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THE ORIGIN AND STRUCTURE OF THE ROXBURY CONGLOMERATE.

By George Rogers Mansfield.

With Seven Plates.

CAMBRIDGE, MASS., U. S. A.:

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F. E. BEDDARD. The Earthworms.
H. B. BIGELOW. The Medusae.
R. P. BIGELOW. The Stomatopods.
S. F. CLARKE. The Hydroids.
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G. W. MÜLLER. The Ostracods.
JOHN MURRAY. The Bottom Specimens.
MARY J. RATHBUN. The Crustacea Decapoda.
HARRIET RICHARDSON. II.[2] The Isopods.
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TH. STUDER. The Alcyonaria.
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R. WOLTERECK. The Amphipods.
W. McM. WOODWORTH. The Annelids.

[1] Bull. M. C. Z., Vol. XLVI., No. 4, April, 1905, 22 pp.
[2] Bull. M. C. Z., Vol. XLVI., No. 6, July, 1905, 4 pp., 1 pl.
[3] Bull. M. C. Z., Vol. XLVI., No. 9, September, 1905, 5 pp., 1 pl.
[4] Bull. M. C. Z., Vol. XLVI., No. 13, January, 1906, 22 pp., 3 pls.
[5] Mem. M. C. Z., Vol. XXXIII., January, 1906, 88 pp., 96 pls.
[6] Bull. M. C. Z., Vol. L., No. 3, August, 1906, 14 pp., 10 pls.
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GEOLOGICAL SERIES, Vol. VIII, No. 4.

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No. 4.— *The Origin and Structure of the Roxbury Conglomerate.*

By George Rogers Mansfield.

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Acknowledgments

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Explanation of Plates

Introduction.

Definition.—The term Roxbury Conglomerate is applied to a series of ancient sediments which occupy a large part of the so-called Boston Basin. The series consists of arkoses and coarse and fine conglomerates, interbedded with sandstones and shales or slates. One of the conglomeratic members is well developed and exposed in Rox-

bury, where it has long been known as the "Roxbury Pudding-Stone." Since this rock is, on the whole, one of the most important and characteristic members of the series, its name has been extended to include the entire formation.

Accompanying the Roxbury Conglomerate are contemporaneous intrusions or outflows of basic lava that are intimately related to the sedimentary series. These constitute a problem by themselves and will be discussed in this paper only in a general way.

Areal Boundaries.— *Maps.* The earliest map of the Roxbury Conglomerate that has come to the notice of the writer was published in 1818 by J. F. and S. L. Dana in connection with their Outlines of the mineralogy and geology of Boston and its vicinity. On this map the conglomerate, designated as graywacke, appears as a belt about two miles wide and eight or ten miles long, extending in an east-southeast direction. In President Hitchcock's map, published in 1833 (E. Hitchcock, a), the conglomerate, still called graywacke, is represented as a somewhat oval area with a southwest prolongation through South Natick. The only map that gives the boundaries of the region as a whole with any detail is Crosby's geological map of eastern Massachusetts, published in 1877. In later years the same writer has published more detailed maps on a larger scale of the southwestern parts of the area, Nantasket and Cohasset (1893) and Hingham (1894). The southwestern extension of the conglomerate has been mapped in outline by Tilton (1895). These later studies, together with the work of Burr and the unpublished data collected by a number of students of advanced geology at Harvard University show that some modifications of Crosby's earlier map are necessary but that in the main its outlines are substantially correct. In the preparation of the map accompanying the present paper (Plate 7) all these sources of information have been consulted, together with further papers by Professor Crosby and others and the field notes of the writer.

The Northern Boundary. The true northern boundary of the Roxbury Conglomerate series is enveloped in some obscurity on account of the uncertainty regarding the age and stratigraphic position of the Cambridge and Somerville slates. The latter are regarded by Crosby and others as conformably overlying the conglomerate and forming part of the same series with it; but there is room for a difference of opinion and the matter cannot be regarded as definitely settled. On the supposition that the slates form the upper members of the conglomerate series, the northern boundary of the area is marked by a

well defined and fairly regular escarpment of crystalline and metamorphic rocks which extends southwest from Malden and Arlington to Waltham. Thence the boundary turns more nearly south toward Auburndale and the slate belt becomes interrupted or reduced to a narrow zone which passes southwest by Newton Lower Falls to Wellesley and South Natick. The conglomerate does not extend north of the Charles River, though a single outcrop of a slaty rock with a few scattered pebbles does appear in Watertown between Mount Auburn and Belmont Streets. The northern boundary of the conglomerate extends from Allston and Brighton almost due west in a fairly uniform line to Auburndale. Thence it also passes southwest by Newton Lower Falls to Wellesley and South Natick. With it is associated melaphyr in discontinuous masses. The surface in this western area is largely covered with glacial deposits but occasional outcrops seem to indicate that the conglomerate series continues beneath.

The Southwest Extension. On Crosby's map the southwest extension is represented as a narrow tapering tongue extending from Newton Lower Falls to South Natick, with an eastward prolongation to Charles River Village. Tilton's work in this area seems to show that the boundary is more irregular than that given by Crosby and that the sedimentary zone is wider and extends farther south. The southernmost outcrops of conglomerate occur half a mile northeast and southeast respectively of Farm Pond. On the accompanying map the boundaries are given essentially according to Tilton's mapping, except that on the eastern side the line passes northeast, without bending south to Dover, to the Charles River, about three-quarters of a mile west of Charles River Village. This change is made on account of the fact that the occurrence of granite on the north side of the Charles River just where the latter is crossed by the boundary line and also at a point about three-quarters of a mile west-southwest of Dover makes it probable that the low ridge in that vicinity is composed of granite. The eastward extension at Charles River Village is made to include a large mass of melaphyr and a breccia that may be igneous or sedimentary, or partly both. In places the breccia becomes conglomeratic but even where this is not true the rocks appear to possess a greater affinity to the rocks of the basin than to the felsite breccias. From Charles River Village the boundary line passes north around the western side of the Needham felsite area and thence east to the north of Highlandville, where it joins the southern boundary of the main conglomerate area.

The Southern Boundary. The same obscurity that prevails in the case of the northern boundary recurs at the southern. The slates that border the conglomerate mass on the south are apparently identical with those on the north and the same question as to age and stratigraphic position again arises. On the supposition that the slates are conformable with the conglomerates and overlie them, the southern boundary of the formation lies along the northern edge of the granite area that stretches almost due west from Quincy through Milton Center nearly to Hyde Park. There it bends southwest toward the Neponset River. Whether the boundary around the western end of the Blue Hill Range is continuous with the conglomerate formation that lies to the south is not certainly known. The broad open valley of the Neponset River at this place and the occurrence near Green Lodge of an outcrop of dense silicious sandstone would seem to favor this view but the deep cover of drift and alluvium effectually prevents any definite tracing of the formation across from the northern to the southern area. The occurrence of slate patches on the granitic area near Quincy and of isolated outcrops of slate in Hyde Park, both said to be cut by granitic dikelets and stringers, renders the correlation of the slate with the conglomerate doubtful. Some of the slate at least appears to antedate the conglomerate but how large a proportion of the southern slate belt is included in the earlier formation cannot be determined on account of the heavy drift cover. Professor Crosby believes that all the earlier slate is confined to the Hyde Park locality (p, p. 41) and to the patches on the granite (n, p. 428). The main slate area he classes with the conglomerate series. On the accompanying map the slate belt has been represented as a unit approximately in accordance with Professor Crosby's view. Eastward, according to Crosby (n, p. 439, 508), the boundary forms almost a direct line to Weymouth Back River. There it bends southeast toward a point half a mile south of Hingham Harbor. Farther east the boundary line coincides in general with Weir River between Hull and Cohasset.

Westward the conglomerate appears at Dedham about a mile west of Readville. Thence the boundary bends northwest for about two miles, then turns east-northeast in an irregular line through the southern part of the Stony Brook Reservation and Hyde Park to Mattapan. From that point it again bends westward for about eight miles to Highlandville where it makes another eastward jog of a mile and a half before making the final turn west to join the eastern boundary of the southwest extension.

Area. On the supposition that the slates of Somerville and the

Neponset region are part of the conglomerate formation, the area has the shape of a somewhat distorted obtuse triangle, with a base nearly thirty miles long and an altitude of twelve or thirteen miles. The total area, therefore, is about 120 or 130 square miles, of which the doubtful slates constitute more than one-half.

Neighboring Conglomerates.— *Other Areas.* South of the Blue Hill Range in the so-called Norfolk County Basin lies another relatively narrow belt of sediments which bear many resemblances to the members of the Roxbury series. These rocks are known to be connected through a narrow pass at Sheldonville with the conglomerates and other sediments of the Narragansett Basin. The latter series occupies a large part of the state of Rhode Island and includes a portion of southeastern Massachusetts but it is separated from the Norfolk Basin sediments, except at Sheldonville, by an area of crystalline rocks.

Small areas of conglomerate occur in the basin of the Parker River in Essex County, at Bellingham, and Harvard, Massachusetts, and at Woonsocket, Rhode Island.

Lithological Relations. The Norfolk Basin sediments consist of arkoses, coarse and fine conglomerates, sandstones, and slates that are much like the Roxbury series, though it may be said that on the whole the former have a more marked tendency toward a red color. The pebbles of the conglomerates in the two regions are composed of the same substances, with the exception of the Blue Hills porphyry, which is said to occur on the south side but does not certainly appear on the north side of the Blue Hill Range. Moreover, the only organic remains thus far discovered in the Roxbury series are casts of tree trunks that are similar to forms found in certain portions of the Norfolk Basin. It has been stated that on the north no direct connection has been traced between the Norfolk Basin sediments and the Roxbury series. It was noted, however, that near Green Lodge (Plate 7, Dedham IV, E 16), about in the line of the Blue Hill Range projected westward, there is a limited outcrop of sandstone. The rock in question is greenish gray in color, silicious and similar to some members both of the Roxbury and Norfolk Basin series. But it is much indurated and is penetrated by quartz veins. Possibly it may be a remnant of some earlier formation that furnished material to the conglomerates and formed part of the floor upon which they were deposited. It may be connected with the older slates or it may represent a sandy member of the conglomerate series. Thus no determinative value can be

attached to its occurrence even though it lies in a critical position with reference to the two basins. The evidence furnished by the valley of the Neponset River, apparently excavated in weak rocks which appear to pass from the northern to the southern basin, is equally suggestive and unsatisfactory. While therefore there seems to be reason for believing that the two basins are connected, the existence of the connection cannot be definitely established from the evidence now at hand.

The Narragansett sediments are characterized in some of their members by a considerable intensity of red color. In this respect they greatly exceed the Roxbury series and generally also the rocks of the Norfolk Basin. They consist of arkoses, coarse and fine conglomerates, shales, and sandstones. In general appearance they are much like the rocks of the Boston and Norfolk Basins but they are more highly fossiliferous and in some parts of the series are marked by fossiliferous pebbles and by pebbles containing a considerable amount of white mica. Muscovitic rocks are not known to be represented in the Roxbury and Norfolk Basin series. Here again sediments of similar character but of different ages are found in close proximity to each other but fortunately the fossils contained in them furnish means of identification.

The sediments of the Parker River Basin, so far as known, occupy but a small area in comparison with that represented by the series already mentioned. According to Crosby (b, p. 267–268), they appear to consist largely of slate but there is some schistose conglomerate resembling that at Milton or at South Natick. They are accompanied by igneous breccias and amygdaloid in somewhat the same manner as are the rocks of the Boston Basin. Their color, however, is more intense than that of the Roxbury series in general and more closely resembles that of the strata exposed at South Natick and at Charles River Village.

The Bellingham Conglomerate occupies only a small area a few miles northwest of the Narragansett Basin. It is believed by Crosby to be the stratigraphic equivalent of the Harvard Conglomerate and it has undergone remarkable deformation, whereby the pebbles have been elongated into spindle-shaped and pencil-like masses (ibid., p. 148).

At Harvard, Mass., a wedge-shaped area of conglomerate not more than a few hundred feet wide at its broadest part extends about two miles south from a little north of the center of the town. The pebbles, consisting of quartzite and argillite, are flattened, bent, and drawn

out into lenticular masses. In its general aspect and composition this rock does not resemble those of the Boston, Norfolk, or Narragansett Basins.

The Woonsocket Conglomerate also occupies a rather limited area and is characterized by such a high degree of metamorphism that its composition is often not clearly distinguishable. Here too there is little apparent resemblance to the rocks of the basins east and south.

Age Relations. The age of the Roxbury Conglomerate has not been determined with accuracy. Among its pebbles granitic fragments are common. Granite of the Quincy type has been shown by Wadsworth to be intrusive into the Braintree slates (b, p. 275), which have yielded Middle Cambrian fossils, *Paradoxides harlani* Green (W. B. Rogers, a, p. 27–29, 40–41). Pebbles of another type of granite, whose relations to the Quincy granite are not certainly known, are abundant in the conglomerate. Crosby believes the granites in question to be differentiation products of a single batholite (n, p. 311 et seq.). The slates at Hyde Park are cut by granite dikelets and felsite (Crosby, p, p. 42) so that the conglomerate which contains pebbles both of felsite and of slate must be younger than both of these rocks. The Quincy granite is therefore of later age than the Middle Cambrian. The discovery at Forest Hills of what are believed to be fossils has not thrown much light on the subject of the true age of the conglomerate. The forms in question, as described by Burr and Burke, occur in a sandy zone near the top of the conglomerate series. They are cylindrical in form, with circular cross-sections, and are believed to be casts and moulds of trunks or roots of tree-like forms. The largest has a maximum diameter of 4.8 inches and all are marked by somewhat irregular transverse wrinklings. No organic matter is preserved. (Burr and Burke, p. 180). The only characteristic features are the transverse markings and it is possible that even these may be of mechanical origin. Assuming organic origin as the most probable explanation of these forms they still have no determinative value for they may have been derived from Devonian or Triassic as well as from Carboniferous life (ibid., p. 181–183).

Moreover, in the consideration of the age question the possibility of the presence of unrecognized upper Cambrian or Silurian rocks in the region must be kept in mind, as well as the fact that the formation may represent more than one geological period. Nevertheless the occurrence of granitic pebbles in such abundance in the conglomerate shows that a long interval of erosion must have succeeded the period of granitic intrusions, for granite is usually a deep-seated rock and its

exposure to pebble-making agencies suggests the removal of a heavy sedimentary covering. This consideration, together with the close resemblance of the Boston Basin sediments to the rocks of the Norfolk and Narragansett Basins, in which undoubted Carboniferous fossils have been found, have led many geologists to believe that the Roxbury Conglomerate is also of Carboniferous age.

In the Norfolk Basin casts of tree trunks have been described by Crosby and Barton and by Woodworth as occurring near Pondville, Mass. (Crosby and Barton, p. 416–420; Woodworth, b, p. 145). The writer too has found irregular cylindrical cavities, unlike pits formed by the removal of pebbles from the conglomerate and comparable to casts made by irregular stems or roots of plants. The forms referred to occur in a gritty zone in a ledge about 200 yards southwest of the residence on the top of the ridge, a mile south of the intersection of Green Lodge Street with the eastern side of the Neponset valley. One of the supposed fossils is exposed on the front of the ledge and measures two feet in length with a breadth and depth of three and five inches respectively. The front part of the cast is broken away and the inside is marked by transverse wrinklings after the manner of the fossils found at Forest Hills. In this case, however, it is not certain whether the markings are original impressions or only due to weathering along the shear planes which cut obliquely across the cavity. The wrinklings are not well developed on the north side. The other supposed cast is found on the top of the same ledge. A hole two or three inches in diameter with somewhat elliptical cross-section was dug out with a knife to the depth of six or eight inches without showing any diminution in size or any bottom. The shape of the cavity is irregular and unlike that of any of the pebbles seen in the rock, but is such as might well be expected in the cast of a root or somewhat irregular stem. Both forms lie in the plane of the bedding, which is here nearly vertical, and they must have been practically horizontal at the time of their deposition. Well-defined Carboniferous fossils, however, have been found by Woodworth toward the southern part of the basin in the railway cut north of Canton Junction (Woodworth, b, p. 146).

In the Narragansett Basin beds of coal occur at several localities and a number of insects and plants have been identified. Some of these have been compiled and tabulated by Woodworth in his report on the northern part of the basin (d, p. 202–204). From a study of the flora of the Rhode Island coal measures Lesquereux concluded that the latter were equivalent to beds of the Upper Carboniferous in Pennsylvania (ibid., p. 204).

The conglomerate at Harvard is intimately associated with the so-called phyllite, which is graphitic in a number of places and at Worcester contains the coal mine in which a Lepidodendron was found. The Worcester phyllite is therefore considered Carboniferous and the Harvard Conglomerate is believed by Emerson, who has worked in the Harvard region, to be also of Carboniferous age.[1]

No reliable data are at hand with reference to the ages of the Woonsocket, Bellingham, and Parker River Conglomerates. The only clues are furnished by their lithological resemblances to the other conglomerate formations of the region.

It is thus seen that the Narragansett and Norfolk Basin sediments are definitely known to belong to the Carboniferous period and that there is a strong presumption that the Roxbury series is of similar age. In the case of the outlying conglomerate masses there is no definite evidence, but it seems likely that these rocks may also be Carboniferous.

Unity or Diversity of Origin. In view of the close lithological resemblance of the Roxbury Conglomerate to the sediments of the Norfolk and Narragansett regions, the basin-like occurrence of each group of strata and the known Carboniferous age of the Norfolk and Narragansett rocks, it seems unlikely that the separate sedimentary areas could have had diverse modes of origin. On the contrary, since the entire area in which these rocks lie is relatively small, it seems probable that similar causes operated to produce similar results in each case. Moreover, since the more westerly areas are possibly also of Carboniferous age it may be true that they too have been formed by similar agencies. The Roxbury Conglomerate has been the writer's chief study, but its history is perhaps similar to that of the other areas and is thus of more than local significance. The data furnished by the other areas may in turn throw light on the history of the Roxbury Conglomerate. Therefore an account of the origin and structure of the Roxbury Conglomerate must take into consideration the neighboring similar formations.

Broad and Narrow Terrane Views. Whatever may have been the agencies that produced the conglomerates the latter may be conceived either as material originally deposited in separate, circumscribed areas or basins of not much greater extent than those they now occupy, or as uneroded remnants of a great formation that has largely been removed. The former view implies an ancient topography not very different from that of the present time, while the latter involves the uplift and

[1] Conversation with the writer.

removal by erosion, and perhaps also by displacement, of great masses of rock. The former idea may be called the narrow terrane view, the latter the broad terrane view. According to the narrow terrane view the Boston Basin and the Narragansett-Norfolk Basin may be considered as originally adjacent though separated areas of deposit or as separated members of one originally continuous basin. In either case, however, it is presumed that the combined area now occupied by the deposits of the several basins is approximately the same as that of the original deposit and that the latter was never very extensive. According to the broad terrane view the present deposits are down-folded or down-faulted remnants of a great mass of sediments which originally extended far beyond the present limits of the conglomerate areas but which have been removed by elevation above the plane of erosion or have been submerged beneath the sea.

One of the strongest supporters of the narrow terrane view was Professor Crosby. In his Contributions to the geology of eastern Massachusetts he says (b, p. 181): "The Paleozoic rocks of eastern Massachusetts occur. . . .only in limited basins or depressions excavated in the ancient crystalline formations. Three of the basins have been recognized, and they are almost as well marked in the modern as in the ancient topography: for I hold the view that these basins probably existed as such before the deposition of the sediments which they contain." The results of later studies, showing the probable close relationship of the rocks in the three basins mentioned, have compelled a change of view so that the same author in a later paper speaks of the conglomerate as having been spread "far and wide over the entire region" (n, p. 464). Professor Shaler also speaks of the area of deposition as a "broad trough penetrating far into the land, possibly including the Worcester trough" (Shaler et al., p. 9).

Views of Origin.—The conglomerates have been very generally believed to be of marine origin. In fact up to twenty-five or thirty years ago there appears to have been no suggestion of any other possibility. One of the earlier hints of dissent from the common view is given by Dodge in his Notes on the geology of eastern Massachusetts. He speaks of the similarity of some features of the Roxbury Conglomerate to those of glacial deposits and suggests in a merely tentative way the glacial origin of the conglomerate (a, p. 408–409). The glacial hypothesis is vigorously combated by Crosby in his Contributions above referred to, where he maintains the hypothesis of marine origin (b, p. 187). Later Shaler advocated the

idea that the conglomerates of eastern Massachusetts represent ancient glacial material worked over by the sea (Shaler et al., p. 57). Another view, suggested by Bouvé, (b, p. 40–41) is that the conglomerates were formed of rock deeply disintegrated under the "highly corrosive" atmosphere of early ages and subsequently resorted and deposited by waves. The possibility of fluviatile origin for the Roxbury Conglomerate has not been suggested in published accounts, but Professor Woodworth has shown (d, p. 176–177) that some portions at least of the Narragansett sediments were deposited by streams, and in conversations with the writer he has often expressed the opinion that the entire conglomerate series of eastern Massachusetts is non-marine. The later published views, however, still regard the conglomerates as laid down by a transgressing sea, during a period of slow subsidence of the land, accompanied by various oscillations in level (Crosby, n, p. 461). Similar conclusions were reached by La Forge in his unpublished report on the Geology of Somerville (p. 90). The current tendency of opinion therefore seems to be to regard the conglomerate as marine, but it must be admitted that the other hypotheses have not been examined with sufficient care. In the present paper an attempt will be made to consider carefully various hypotheses in order to determine if possible which has the greatest weight.

Scope of Field Work.— The Roxbury Conglomerate is abundantly exposed in a number of separated areas. An attempt has been made to see the principal outcrops in each of these regions, with the idea of getting a general view of the whole field rather than of making a detailed study of particular areas. The work has also included a similar, though not so extended, study of the Norfolk Basin sediments. Several trips have been made into the Narragansett Basin, more especially to the districts in the vicinity of Attleboro, Seekonk, Tiverton, and Newport, and localities near Worcester and Harvard, Massachusetts, have also been visited, the latter in company with Professor Jaggar. The Parker River, Bellingham, and Woonsocket areas have not been seen by the writer.

Scope of Laboratory Work.— Numerous selected specimens collected by former students in geology at Harvard University and by the writer, from typical localities, have been examined and studied. Their character and composition have been determined by means of a low power lens on natural and polished surfaces and

higher power lenses with thin sections. The data thus obtained have been compiled and tabulated, together with data derived from field observations.

The Origin of Conglomerates.

General Statement.—Before taking up the question of the origin of the Roxbury Conglomerate it was necessary to find criteria by which to judge whether these rocks should be ascribed to marine action or to some other mode of formation. An investigation of the literature has accordingly been made to determine the characteristics of other conglomerates in various parts of the world, ascribed to this or that mode of origin. An attempt has been made to examine all the more important papers bearing on the subject, but the limitations of time make it possible that a number of valuable sources of information have been overlooked. The present chapter embodies citations in which the characteristics of certain types of conglomerate are set forth by various writers, together with a discussion and classification of the criteria thus obtained. Before entering upon the discussion of particular types of conglomerate it is desirable to note the characteristics of conglomerate in general and of certain allied types of rock. To that end a few definitions and brief descriptions are given here substantially as in Geikie's Text-book of geology.

Definitions and Descriptions.—*Conglomerates.* Rocks formed of consolidated gravel or shingle are called conglomerates. The component pebbles are rounded and waterworn and may consist of any material, though usually of some durable kind, as quartz or granite. Different names are given to conglomerates according to the character of the pebbles contained, as quartz or granite conglomerates; or according to the nature of the cementing paste or matrix, which may consist of hardened sand or clay and may be silicious, calcareous, argillaceous, or ferruginous.

The bedding is not always distinct and it may sometimes be necessary to view the rock as a whole in its relations to the overlying and underlying beds before its stratified character can be conceded (A. Geikie, p. 63). The size of the constituent pebbles may range from masses several feet in diameter through shingle and gravel of successively finer texture until the rock becomes a grit or a coarse gray-

wacke. The relative proportions of pebbles and matrix may also vary from a rock consisting of practically nothing but boulders to a pebbly sandstone. Variations in bedding may also occur so that strata may suddenly sink from a thickness of several hundred feet to a few yards, or may die out altogether, perhaps to reappear in the same wedge-like fashion. Conglomerates are thus, as Geikie well says (ibid., p. 651), "the most variable and inconstant of all sedimentary formations," but whatever irregularities may occur the pebbles maintain some degree of rotundity.

Breccias. Allied to conglomerates and sometimes shading into them are rocks composed of angular instead of rounded fragments — breccias. They commonly present less marked stratification than conglomerates and have been only slightly, if at all, affected by running water. Various agencies may produce breccias, which are named according to their mode of origin. The normal breccia is formed by the accumulation of the products of the superficial decay of rocks, without the intervention of water action, save that involved in the rapid deposition of material launched from steep slopes or cliffs into a lake or the deep sea. Angular blocks and fragments accumulated around vents may become consolidated into *volcanic breccias.* Igneous eruptions may tear off fragments of the rocks through which they pass or may break through previously consolidated portions of the igneous rock, thus forming, when the mass solidifies, *igneous breccias.* Movements of rock masses along fracture planes sometimes produce a zone of angular fragments which, by subsequent infiltration and deposition of mineral matter, becomes a *fault breccia* (ibid., p. 164).

Agglomerates. Tumultuous assemblages of blocks, of all sizes up to masses several yards in diameter, occur in the necks or pipes of old volcanic openings. The stones and paste usually consist of one or more volcanic rocks; but they may sometimes include fragments of the rock through which the orifice was drilled. Such accumulations are called *volcanic agglomerates.* As a rule they are devoid of stratification but they may sometimes include coarser and finer materials arranged in more or less distinct beds, which are often placed on end or inclined at a high angle. The last feature is probably due to the subsidence of beds of tuff within the crater and upper part of the funnel (ibid., p. 174, 751).

Volcanic Conglomerates. When the coarser volcanic fragments become rounded by attrition within the crater or funnel, and especially when they are resorted and deposited by moving water, the consolidated accumulations formed are called volcanic conglomerates (ibid., p. 276).

This chapter is concerned chiefly with the characteristics of true conglomerates as determined by their modes of origin but it includes a discussion of certain rocks that have been named and described as conglomerates, although in the light of the above definition they would more properly be classed under another heading (see, for example, the Dwyka Conglomerate, p. 130).

Types of Conglomerate.— The principal types of conglomerate that will receive consideration are: (1) marine; (2) fluviatile; (3) estuarine; (4) lacustrine; (5) glacial. To these may be added the pseudo-conglomeratic rocks produced by internal movements of the strata and called (6) crush-conglomerates. Moreover, (7) it should be remembered that many combinations of processes are possible and that many accumulations doubtless owe their origin to such combinations.

Marine Conglomerates:—Cretaceous of Texas. One of the best examples of marine strata is the Cretaceous system of Texas, so well described by R. T. Hill. A persistent feature of this system is the formation known as the Basement or Trinity Sands. They are said (R. T. Hill, p. 132) to be usually accompanied at the base by a fine pebble conglomerate. At one of the places mentioned (ibid., p. 141), where the basal beds are locally known as the Sycamore Sands, the matrix of the conglomerate is described as a "cement of ferruginous, yellow and red, gritty sand." The material of the pebbles in the conglomerate varies locally according to the nature of the adjacent, pre-existing rocks (ibid., p. 132) and may consist of masses of limestone, quartz, chert, granite, and schist, four to six inches in diameter at the base and decreasing in size upward. They are well rounded at the locality above mentioned (ibid., p. 141) but elsewhere (ibid., p. 181–182) many of the cobblestones are described as but slightly worn. In the latter case the basal conglomerate consists chiefly of limestone, sandstone, and chert of local derivation, while quartz pebbles from more remote sources are smaller and well rounded. The conglomerate bed exposed in Pompey and Blanket Creeks (Brown County) is described as furnishing a fine illustration of false bedding (ibid., p. 183).

The Basement Sands contain thin beds and laminae of red and blue clay (ibid., p. 132). The Denison beds of the Washita division also contain ferruginous clays and as a whole they are said to be "characterized by the strong ferruginous colors peculiar to near-shore deposits" (ibid., p. 266).

The basal conglomerate grades upward into sands, false-bedded

shell grits and silts (ibid., p. 109, 141) and seldom reaches the thickness of 200 feet (ibid., p. 133). In some places the bedding is massive but elsewhere sands and clays are interstratified with the conglomerate, though the stratification is not well marked, and again false bedding becomes more common (ibid., p. 182–183). Sometimes the interstratified clay is in lenticular layers or even in balls (ibid., p. 198). Variations in thickness and in composition along the dip of the several beds are much greater than along the strike and all the beds are more or less lens-shaped in cross-section, first thickening and then thinning seaward (ibid., p. 370).

The extent of the Basal Sands is a noteworthy feature. They were deposited successively farther inland during the transgression of the sea and hence underlie beds of varying age from older to younger, into which they pass horizontally as indicated in Figure 1, taken from

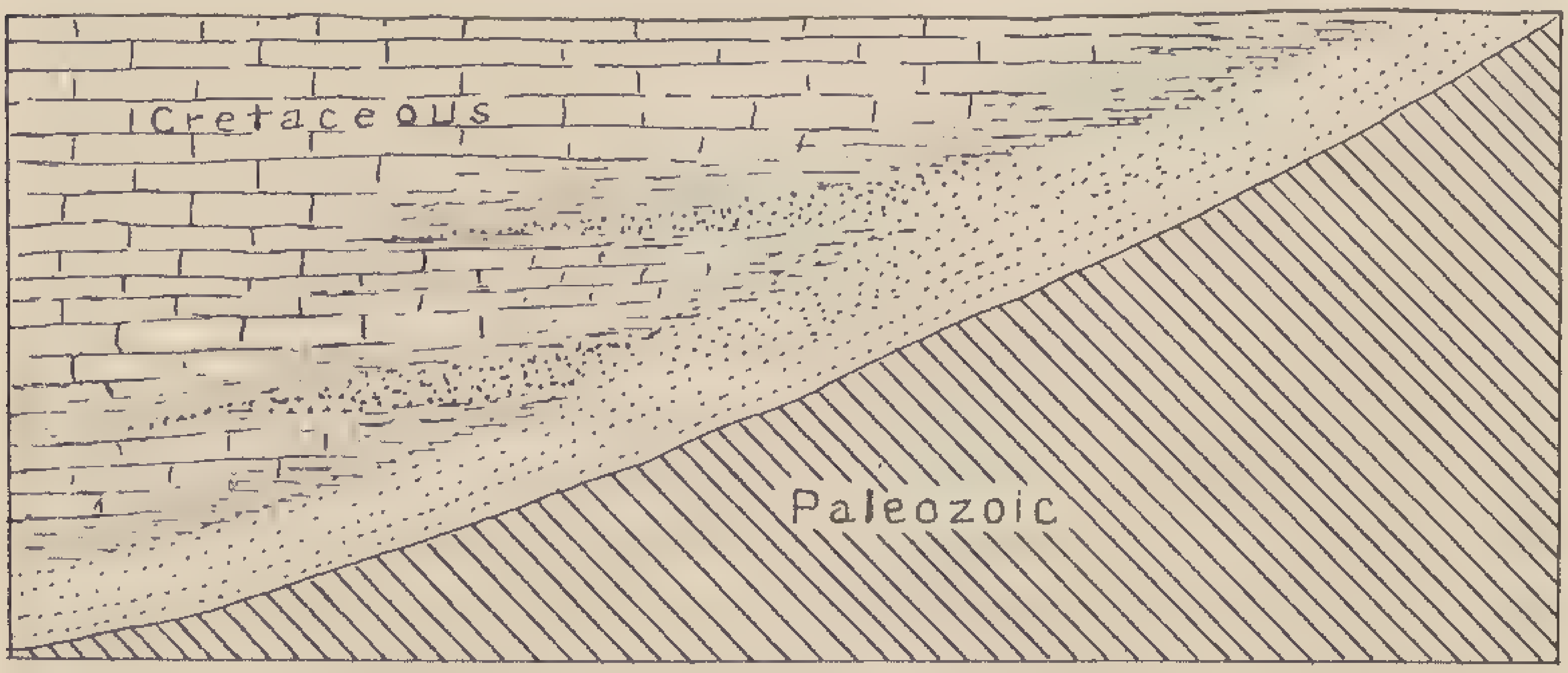

Fig. 1.— Diagrammatic section of the Basal Sands of the Cretaceous of Texas, showing the normal arrangement of sediments with an encroaching sea (slightly modified from R. T. Hill, p. 202).

Hill's description (ibid., p. 202). They thus have great extent yet throughout they maintain a remarkable similarity and uniformity in lithological nature (ibid., p. 179).

The Cretaceous system of Texas rests unconformably upon the planed off edges of different layers of Palaeozoic rocks that had endured a long period of erosion (shown by the absence of Triassic and Jurassic sediments) and had probably been reduced nearly to base level. The ancient land surface of that time has been termed by Hill the "Wichita paleoplain." Irregularities of configuration of this Precretaceous land are shown by some degraded remnants that still persist, like the Ouachita Mountains (ibid., p. 363).

——: —*Pottsville Conglomerate.* The Pottsville formation of Pennsylvania and the region southward has been ascribed to marine origin. Accounts of it have been given in the state reports and in various separate papers. According to David White the rocks consist of ponderous conglomerates, which are more variable in color, composition, and assortment in the lower part and more quartzose, dense and light colored near the top. The conglomerates alternate near the base with washes of purple and olive mud or soft greenish sandstone, and in the higher portion with thin arenaceous shale and coal seams (D. White, a, p. 762). The section in Sharp Mountain below Pottsville shows a transition from the Mauch Chunk to quartz conglomerates. The conglomerates intercalated in the upper beds of the Mauch Chunk are irregularly bedded and poorly assorted or sometimes apparently unassorted pebble or boulder accumulations in a matrix of coarse arkose sands, colored by reddish or greenish shale washes. The pebbles are mostly quartz though other crystalline and clastic rocks are also present. Occasionally the pebbles, which are sometimes subangular, attain a diameter of three or four inches but usually they do not exceed the size of a goose egg. For a long distance from the base the conglomerate matrix consists of micaceous, chiefly arenaceous material, poorly cemented and often colored with red or green argillaceous matter. Irregularities of bedding and variety of rock constituents in the pebbles, which often are imperfectly rounded, are interesting features of the lower portion of the Pottsville formation. Subangular pebbles in imperfectly bedded arkose conglomerates are not rare throughout the lowest third (ibid., p. 763–764).

The study of fossil plants shows that the Sharon conglomerate, which constitutes the basal member of the Upper Carboniferous over the greater portion of western Pennsylvania and part of Ohio, and which has been regarded as the basal member of the Pottsville in general, belongs in the upper part of the typical Pottsville; and that several thousands of feet of Pottsville sediments in the southern Appalachians and a great thickness of beds in the southern anthracite region were laid down before an encroaching sea began the assortment of Sharon materials in western Pennsylvania or Ohio (D. White, b, p. 268). The thick sections along the eastern border of the Appalachian coal region contain floras distinctly older than those present in the lowest beds of the thin northwestern sections and the characteristic floras of the thin sections occur in their natural order in the upper part only of the thick sections (ibid., p. 271).

The Sharon (Olean) Conglomerate, mentioned in the state reports as "a round pebble conglomerate" (Lesley et al., p. 1721), is described by I. C. White as being everywhere a very massive, coarse, grayish-white, pebble rock, the pebbles varying in size from a pea to a hen's egg, all cemented into a matrix of coarse gray sand, and frequently containing vast quantities of imbedded plant remains (I. C. White, p. 37).

The thickness of the Pottsville Conglomerates in the anthracite district averages 1200 feet in Carbon, Schuylkill, Lebanon, and Dauphin counties but it diminishes rapidly toward the north-northwest in Luzerne and Lackawanna counties. The reduction in thickness is accompanied by a decrease in the coarseness of materials; the pebbles become scattered and are no larger than a pea (Lesley et al., p. 1854). Stevenson, who has studied the Pottsville formation from the stratigraphic standpoint, concludes that the thinning out toward the northwest is due to the successive disappearance of the lower members, so that in much of the northern field even the Sharon sandstone has but an insignificant representation (Stevenson, p. 202). Thus his results agree with the palaeobotanical studies of David White in placing the apparently basal conglomerates in the thin northwestern sections high up in the columns of the thicker, more easterly sections.

Bailey Willis, after noting some of the characteristics already mentioned, brings out the additional feature of lenticular form, which appears to be common in the Pottsville and later Carboniferous deposits, so that a bed of sandstone, shale, or coal thins out and is replaced in its own horizon by deposits of different texture (Willis, c, p. 73).

It will be noted that the Pottsville formation presents a number of contrasts to the Cretaceous system of Texas. The variability of composition, assortment, and color in the lower members and the rapid diminution in thickness and size of materials toward the north-northwest are especially noteworthy when compared with the relative uniformity of the Texas series over wide areas. Recent unpublished studies by members of the New York State survey throw doubt upon the marine origin of the Pottsville rocks. Professor Grabau, in a recent (1906) unpublished address to the Geological conference of Harvard University, expressed the view that the Pottsville series represent, on the whole, a great alluvial fan, which in its growth extended progressively northwestward. The Pottsville Conglomerate cannot, therefore, be regarded as a typical marine deposit. More probably it should be classed among fluviatile deposits, which in recent

years have been shown to possess a greater geological importance than was formerly accorded to them.

Fluviatile Conglomerates: — India. The great Gondwana system of India, consisting mainly of sandstones and shales with some coal beds and ranging in age from Upper Carboniferous to Middle Mesozoic has been ascribed chiefly to fluviatile action (A. Geikie, p. 1058). With the exception of the Talchir group, which will be described in a later section, there are no conglomerates of importance in the system; but the latter is of interest because it furnishes some means whereby fluviatile sediments may be distinguished from those of other origin. These will be noted later.

The Siwalik group, a Tertiary deposit, exposed in the hills of the same name along the southern base of the Himalayas, has also been ascribed to fluviatile action. The thickness of the series in the hills is at least 1,500 feet, while in the northwest Punjab it is estimated at 14,000 feet (ibid., p. 1207). The group consists of sandstones with interbedded clay bands and some coarse conglomerates with well-rounded pebbles. Some of the finer beds of the lower part of the section are of bright red or of purplish color. The upper Siwaliks are more sandy, only occasionally tinged with red, and toward the top they become conglomeratic in bands that increase in abundance and coarseness. Near the large rivers the uppermost group consists principally of coarse conglomerate composed of rounded boulders of hard rock. The intermediate stretches are composed largely of soft earthy beds precisely similar to the modern alluvium of the plains (Oldham, a, p. 356–358).

The Bhábar or gravel slope that today fringes the outer margin of the hills possesses a remarkable resemblance to the deposits of the upper Siwaliks. The extent and composition of the Bhábar varies with its position. The greatest development is opposite the débouchés of the great rivers, where the deposits consist almost entirely of boulders of hard rocks. In the intervening stretches the composition varies with that of the rocks exposed in the drainage areas of the streams. The pebbles are often subangular, owing to the shorter distance of transportation and less abrasion. They are always less rounded than the hard boulders of the great rivers. The upper Siwaliks vary in development in similar fashion. Where the Sutlej emerges from the hills there are at least 4,000 feet of coarse conglomerates; but in a parallel section barely seven miles away, only about 500 feet of conglomerate appear in the midst of over 3,000 feet of sandy clays (ibid., p. 469).

The present Indo-Gangetic plain constitutes a fluviatile deposit of great extent and thickness. Borings have been made at several localities. The deepest noted by the writer is that at Lucknow, which passes through 1,336 feet of alluvial deposits without showing marked increase or decrease of coarseness or reaching the underlying rock (ibid., p. 176). The prevailing formation is some form of clay, more or less sandy. The older deposits usually contain kankar (an impure concretionary limestone) while the newer generally do not. Sand, gravel, and conglomerates occur but are usually subordinate, except on the edges of the valley, the quantity of sand in the clay decreasing gradually as the distance from the hills increases. Pebbles are scarce at greater distances than twenty or thirty miles from the hills bordering the plain (Medlicott and Blanford, p. 396–397). The surface of the deposit forms a great inclined plane, with slope gradually increasing to as much as fifty feet in a mile next to the mountains. The highest and steepest zone, ten to twelve miles wide, is formed of boulders, gravel, and sand of varying degrees of coarseness (Medlicott, p. 226). We should expect that borings near the southern margin of the plain would show fine sediments near the surface, while near the northern margin coarser sediments would overlie the finer, because the streams deposit the coarsest material where they emerge from the mountains and there the rock area encroaches upon the finer sediments. Four deep borings have been made in the Gangetic plain. Two that are favorably located for the purpose confirm the expectation admirably. The other two are less suitable for reference (Oldham, a, p. 475–476).

The alluvial deposits of the upper Indus region have been described by Drew. In the fans the material is accumulated in a general way in layers, though of peculiar form; not horizontal, but rather in curved coatings. The lateral changes of position of the depositing stream and the partial growth of layers are denoted by false bedding (Drew, p. 448). Some of the fans are made up of semi-angular pieces of stone of material such as hardened shale and slate in masses seldom above the size of an octavo volume; others from granitic mountains are composed of more or less rounded blocks of granite which are often four feet in diameter; but among these there is gravel and sand of the same material. In some cases the material merits the description "unrounded" (ibid., p. 451). If the river alluvium remains relatively stationary the fan gravels encroach and rest upon it. It is more usual for both tributary and main stream to raise their beds so that interstratification occurs at the fan-edge, a lapping for a short distance of

one set of alluvial beds over the other. Some sections show beds of well-rounded materials and of sand among less worn fan stuff. The latter being nearer its source is seldom thoroughly rounded (ibid., p. 450–451). The alluvial plateau of Deosai, which Drew regards as a high level deposit of converging streams that spring from the mountains, has a slope of four degrees for eight or ten miles from the mountains and is composed of stones mostly half rounded, some well rounded and a few angular. The boulders commonly range from one or two feet in diameter down to the size of the fist; but some masses occur six, fifteen, and even thirty feet across. A line of springs indicates the stratification. The alluvium of the main valley consists mostly of clay, often dark or drab, but in some places sandy and elsewhere gravelly or pebbly (ibid., p. 461–464).

——:—*Persia.* According to Blanford's observations in southern Asia, the gravel accumulations attain their greatest dimensions in the drier tracts. The gravel slopes in Persia extend five to ten miles from the base of the hills at an angle of one to three degrees. The greater part of the slopes consist of sand and pebbles, the latter more or less angular and mixed with large blocks. Fragments two to three feet in diameter are not uncommon even one or two miles from the base of the hills (W. T. Blanford, a, p. 496–498). Huntington, from more recent observations in Persia, thus describes the alluvial formations in that region. "The junction between the gravel and silt is very indefinite. They appear to merge in places while elsewhere gravel overlies silt. Outside the band of finer gravel the borders of the plain are formed of coarser gravel, which increases in size and in angle of slope of surface as the mountains are approached. On the very edge the gravel becomes a mere mass of rough angular fragments of all sizes up to more than one foot in diameter and it is hard to say where the coalescing fans of the basin deposits come to an end and the creep from the mountain slopes begins. From Bendun to Bering a smooth plain extends southeast with a uniform slope so gentle that in thirty miles it amounts to but little more than 800 feet. From the mountains to the lake the plain is composed of limestone and slate pebbles, coarse and angular near the mountains, well rounded and small near the lake. It is hard to understand how gravel, though fine, can be transported and spread in a sheet on so gentle a slope" (Huntington, p. 250–251).

Oldham (b, p. 464–465) describes the great gravel fans, found everywhere along the foot of the hill ranges of the drier parts of western and central Asia, in the following terms: "They form a continuous fringe along the foot of the hills and often extend many miles over the

plains. At the upper end they are mostly composed of large fragments, the interstices filled with gravel and sand, but farther from the hills the larger fragments for the most part are left behind and the general texture of the deposits is finer. The pebbles even to the outermost limit generally remain imperfectly rounded, for when streams flow after a rain they are generally so loaded with debris as to be of the nature of fluid mud rather than water and in this the fragments of rock seem to be carried *en masse* without being worn against each other to the same extent as in a mountain torrent.... Another effect of the large proportion of mud and stones moved is that occasional large blocks travel in the moving mass far beyond where their fellows are left behind. Occasional exceptional floods bring down larger blocks than usual, which afterwards are covered by or embedded in material of smaller grain."

——:—*Europe*; *Great Britain*. In the Upper Old Red Sandstone there are thick accumulations of subangular conglomerate or breccia that recall some glacial deposits of modern times. The stones in the conglomerate are usually well rounded even when one foot in diameter. The larger blocks are usually more angular fragments locally derived. The smaller rounded stones have often come from a distance; at least it is impossible to discover any near source for them (A. Geikie, p. 1001). It was thought by Ramsey that the deposits were of glacial origin and his reasons for ascribing them to such a source are given later. It has, however, since been shown by W. Wickham King, Oldham, and others that they are the product of fluviatile action and that glaciers were only indirectly, if at all, concerned in their formation. According to Ramsey the deposits consist of stones embedded in a deep red, marly paste. The stones are mostly angular or subangular with flattened sides and but slightly rounded edges. In one locality none of the fragments exceed six or eight inches in diameter. There are in the immediate neighborhood no rocks answering to a majority of these. He infers, therefore, that some, at least, have travelled twenty or thirty miles (Ramsey, p. 189). At another place the sides of some of the pebbles are not only flattened but are sometimes polished and occasionally scratched (ibid., p. 190). At a third locality the rock is a rudely stratified breccia with some fragments as much as two or three feet in diameter (ibid., p. 194). The area covered is estimated at 500 square miles. Later work in more recently opened quarries at several of the localities noted by Ramsey has been conducted by King, who has shown that Ramsey's argument for a distant source of materials no longer holds. The deposit is rudely stratified

but the beds generally shade off into each other and are not continuous for any distance. The rock exposures separately or in relation to each other exhibit all those characters that may now be seen in the great gravel fans of western and central Asia described above (Oldham, b, p. 464). The striations on the included fragments were thought by Oldham to have been produced by glacial action (ibid., p. 470) but King refers to the alleged glaciated pebbles as slickensided and states that the slickensides occur inside and outside the fragments and in the matrix (King, p. 127).

The origin and source of the Bunter conglomerates of the Midlands and South Devon have been the subject of some controversy. Bonney describes the Bunter group as consisting of two wedge-shaped masses of sand separated by similarly shaped beds of pebbles (Bonney, b, p. 370). There is some uncertainty whether they are of lacustrine or of fluviatile origin but he thinks they are probably the latter (ibid., p. 371). The thick ends of the wedge-like masses point northwest, indicating a source in that direction; but the gradation in size of the included fragments does not agree with that interpretation. The sands of the Bunter group are often false-bedded and occasionally contain well-rolled grains, suggestive of wind action (ibid., p. 373). In a later paper Bonney states that the beds in question are very unlike marine deposits, differing most of all in being at once widespread and thick and so not resembling any shingle beds of which he has knowledge (c, p. 295). Shrubsole describes the pebble beds at Budleigh Salterton in South Devon as consisting of pebbles which lie with their long axes at all angles and not at the angle of rest. The pebbles vary in size from one-half to one inch in length and are not sorted. The shape is variable,— longer than broad, broader than thick, and sub-angular. The evidence does not support the view of the early observers who regarded the pebble bed as a marine beach (Shrubsole, p. 315).

——:— *The United States.* The High Plateaus of Utah, described by Dutton, furnish a remarkable example of extensive conglomeratic deposits ascribed to fluviatile action. The rocks attain a thickness of 2,000 feet over an area of 2,000 square miles (Dutton, p. 69). The fragments range in size from mere grains to blocks weighing several tons. Both fragments and matrix consist of volcanic materials without the admixture of debris from ordinary sedimentary or metamorphic rocks (ibid., p. 74). None of the fragments exhibit the sharp edges of fresh fracture. While well-rounded fragments are uncommon, it is not certain that any noticeable portion of them is absolutely free

from attrition. The average attrition is generally small, far less than that of conglomerates in fossiliferous rocks (ibid., p. 75), and the rock grades into a breccia. The limited attrition may be explained by the scarcity of quartz sand in the detritus of the volcanic rocks. The accumulation is not the product of volcanic explosions (ibid., p. 76) but is derived from the waste of a mass of volcanic rocks under the normal processes of degradation manifested in mountain regions. The material borne by the torrents through the ravines and gorges is spread out over the plains as depressed alluvial cones, so flat or so gently sloping that their conical form is not at first recognizable (ibid., p. 77–78). The rock is susceptible of a peculiar kind of metamorphism. The matrix becomes similar to the included fragments, holds the same kind of crystals and under the microscope generally has the same texture and composition. Crystals are frequently seen lying partly in the original pebble and partly in the original matrix and the surface of fracture shows no inequality of hardness or cleavage. The fragmental character of the material has disappeared (ibid., p. 79–80).

In his discussion of the formation of conglomerates Dutton emphasizes the relatively local nature of all conglomerates by the remark that "it would seem to require extraordinary circumstances to justify the belief that a conglomerate could be formed as far as fifty miles from the source of its fragments, and it is probable that most of the stratified beds are formed in the very neighborhood of those sources (ibid., p. 215). The proportion of coarse materials in one of the broad flat cones becomes greater toward the higher parts of the slope. The stream shifts its course on the cone and builds first one place, then another, but with approximately equal and uniform results. Sections along the radii of a cone give the best stratification. When transverse sections are cut the stratification, though still conspicuous, is much less uniform and harmonious. The cone appears built of long radial or sectoral slabs superposed like a series of shingles or thatches. Cones derived from the waste of sedimentary strata seldom contain coarse debris, while those of harder rocks are largely composed of it (ibid., p. 220–222).

The "High Plains", described by Johnson (p. 612) as uneroded remnants of an extensive debris apron that formerly extended along the eastern front of the Rocky Mountains, constitute another example of extensive fluviatile deposits in an arid region. The apron has been formed by the coalescence of a series of alluvial fans along the mountain front (ibid., p. 615). The development of these fans

shows that in successive periods successive sets of stream threads wandered repeatedly over the whole and that as each "patchwork addition" was but slight the construction was carried forward with substantial uniformity. Every stream has a line of swiftest motion along which its coarsest material is dropped, while on either hand the finer material is deposited. The debris slope, then, was built, not of bedded sheets, as the alternate occurrence of coarse and fine material would seem to indicate, but of interlaced gravel courses penetrating a mass of fine material (ibid., p. 618). The thickness of the deposit sometimes reaches 500 feet (ibid., p. 628). The maximum size of the gravel is that of cobbles but such material is uncommon. Individual boulders of larger size, not well rounded, occur in various places as if transported thither by river ice or uprooted trees. They are often of softer rock, such as sandstone, while the gravelly materials are invariably hard. Finer textured gravels are relatively abundant (ibid., p. 634). The gravels are disposed in courses, following the direction of slope of the plains, and consist of materials that have travelled far (ibid., p. 627) and are well rounded.[1] All sections natural or artificial show a no less frequent occurrence at one level than at another. There is no observed graded variation in size of the gravel up or down in the section but there is a gradual diminution in size from the mountains outward, and the rate of diminution seems the same at all levels (ibid., p. 633). The gravel beds are invariably found elongated in the direction of slope of the plains, or approximately that direction, and are prevailingly cross-bedded. The sand beds have similar structure but are deeper and broader with gravelly courses interwoven (ibid., p. 634). While the coarser materials are important and widespread, fine clay constitutes the bulk of the mass through which the coarser materials extend in layers of varying thickness and at varying intervals (ibid., p. 635). While thicker beds of coarser material occur in the lower part of the sections they are farther apart than in the upper portion. Occasional thick beds appear in the upper levels also (ibid., p. 637). The finer materials have a similar arrangement to that of the coarse. Elongated clay beds are separated by thin sand beds and occasionally by fine gravel. The clay beds are not, however, limited to lenticular shape but frequently appear as thin masses spread between layers of sand or gravel (ibid., p. 638–639).

[1] The illustration facing p. 634 in Johnson's report shows the pebbles as subangular on the whole.

With reference to the large boulders, whose transportation is ascribed by Johnson to river ice or uprooted trees, the observations of Stone go to show that such agents are not required to account for the presence of the boulders. He cites examples of cloudbursts in Colorado where the streams produced were successively dammed by hail, then broke through the obstructions with rapid current and transported slabs of sandstone four feet square and two feet thick. One such stream 200 to 300 feet wide and 20 feet deep (in the deepest place) issued from the narrow valley of Templeton's Gap near Colorado Springs. It became wider on the plain but was swift enough to carry the above mentioned boulders one-third of a mile. Previous to the flood the plain at this point was composed of sand loosely grassed over. The boulders were dropped upon the sand plain which was but little eroded by the swift currents; then, as the flood slackened, sand was deposited upon and around the boulders to the depth of from one to three feet. Numerous similar observations in Colorado show boulders of considerable size surrounded by fine sand and gravel or even embedded in clay. It thus appears that swift currents can flow over a stratum of fine sediments having an even or level surface without eroding much. This is largely due to the fact that the lower part of the water is nearly stopped by friction. The stream cannot get at the sediment while it remains coherent. Stone considers it certain that large stones and even boulders may be deposited by running water in the midst of sediments as fine as sand, or even in clay. The requisite is a rapid current moving over an even surface and acting for a rather short time. (Stone, p. 17–18).

An interesting case of deep fluviatile deposits is that of the Great Valley of California described by Ransome. Borings in the San Joaquin Valley at Stockton have penetrated 2,000 and 3,000 feet respectively without reaching the bottom of the unconsolidated fluviatile sediments. The latter consist of fine sands and clays with occasional beds of coarser sand and gravel (Ransome, p. 381) but there appears to be no definite gradation in size of materials vertically.

Delta Deposits. Where rivers carry sediment into lakes or into those parts of the ocean where the action of currents, waves, and tides is insufficient to sweep away the material delivered by the streams, deltas are formed. An extended account of their surface and structural features, geographical distribution, classification, and origin, together with the effects of elevation and subsidence of coast lines is given by Credner. More recently Gilbert has described their general characteristics in connection with other features displayed by the

abandoned shore lines of the Quaternary lakes of the Great Basin. Where a river joins a lake or the ocean the heavier and coarser part of its load, that which is pushed or rolled along the bottom, is deposited and slides down the front of the delta by its own weight. The slope of the face of the delta is the angle of repose of this coarse material subject to modification by waves. The finer detritus is carried beyond the delta face and sinks slowly to the bottom, the deposit being thicker near the delta and gradually diminishing outward so that the slope of the delta face merges in a curve with the bottom beyond. As the delta is built outward the steeply inclined layers are superposed over the more level strata of the bottom and in turn come to support the gently inclined layers of the delta plain, so that any vertical section

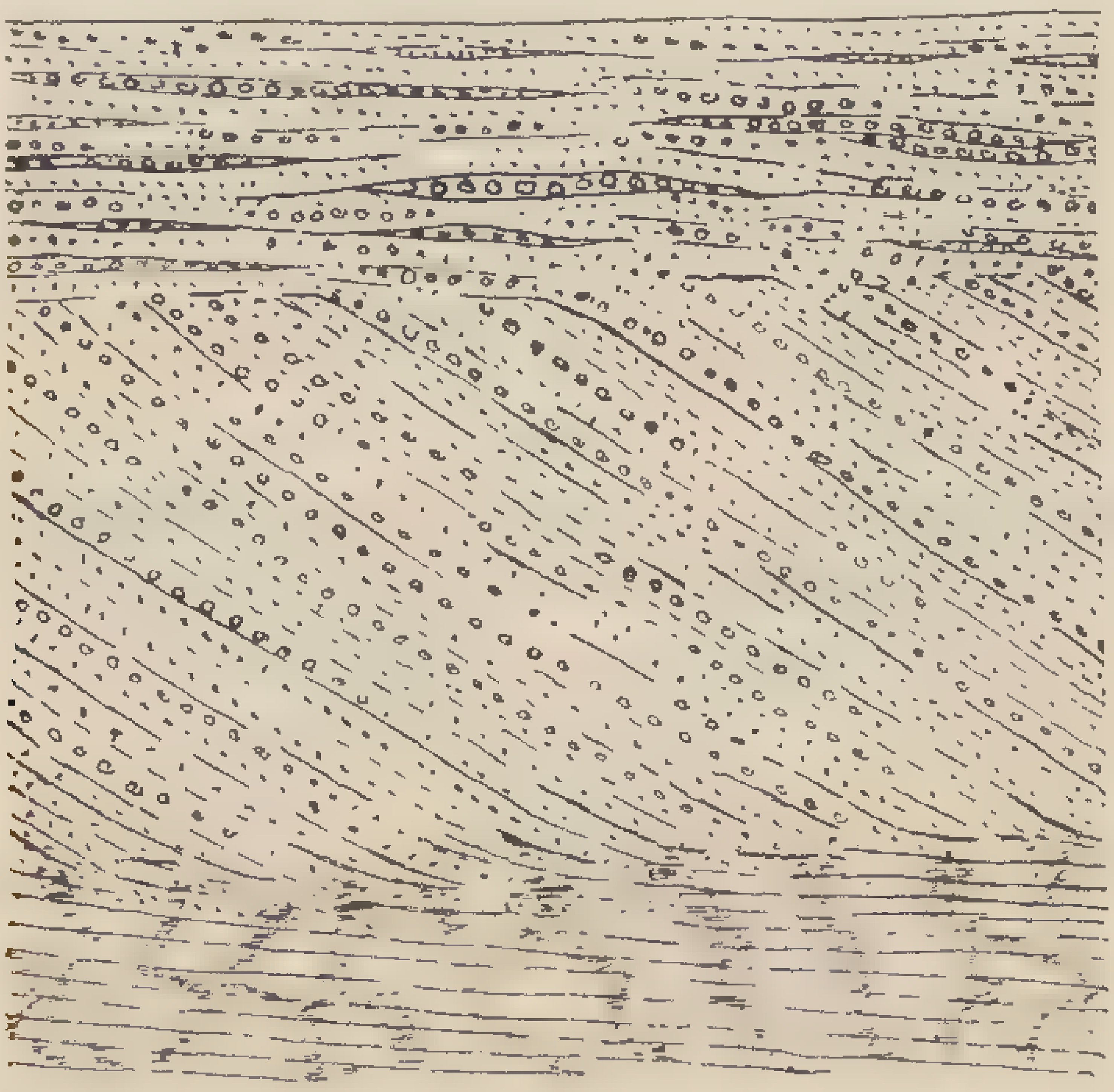

Fig. 2. — Diagrammatic section of delta deposits (slightly modified from Gilbert, a, p. 107).

of a normal delta shows at the top a zone of coarse material, bedded with gentle inclination, then a zone of similar coarse material, the laminations of which are at a high angle and at the bottom a zone of fine material, the laminations of which are gently inclined and unite by curves with the middle zone (Gilbert, a, p. 106). Such a section is represented in Figure 2, taken from Gilbert's description (ibid., p. 107). Sometimes marine sediments are intercalated among the delta deposits, as in the case of the Mississippi delta. Again, deep borings have been made in deltas without encountering any traces of marine conditions. According to Medlicott, the Ganges-Brahmaputra delta

has been bored to the depth of 481 feet. The whole mass was found to consist of fine sands and clays with occasional pebble beds, a bed of peat and remains of trees; but there was no trace of marine organisms (A. Geikie, loc. cit., p. 518). Since deltas are built forward by the deposits of streams and distributaries which may alter their courses from time to time, the bedding will tend to be that of an imbricated series of lenticular masses rather than that of a uniform series of layers.

Lacustrine Deposits. Delta deposits, which are so frequent along lake shores, have been described above. The littoral processes of lakes differ from those of the oceans only in the absence of tides. It is natural, therefore, that the deposits formed by these processes should be essentially similar in both cases. The main effect of the tides upon the deposition of sediments is probably to sort the materials more thoroughly. We should expect, therefore, that lacustrine formations would be, on the whole, less perfectly sorted than marine accumulations. The characteristics of lake sediments have been discussed to some extent by Delebecque in his work entitled "Les lacs Français,"

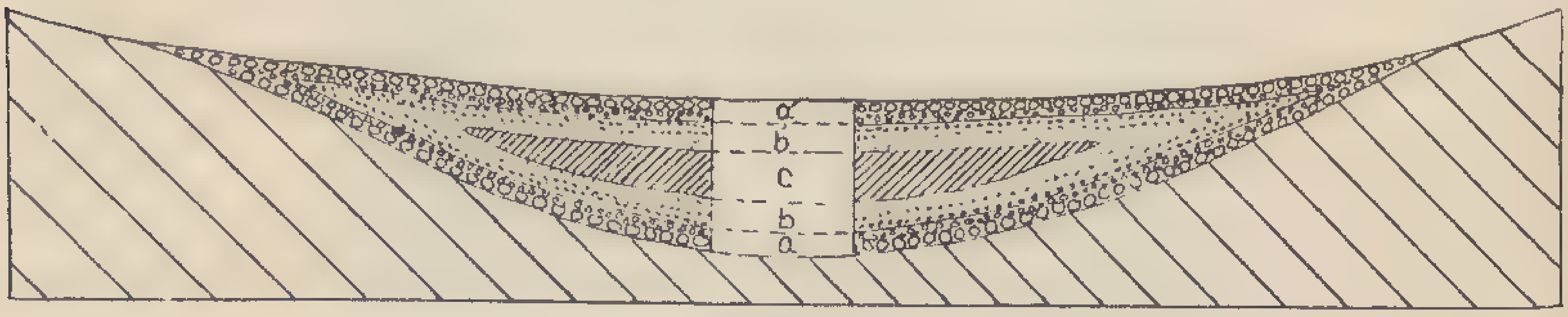

FIG. 3.— Diagrammatic section illustrative of the fresh-water cycle of sedimentation: aa′, coarse gravel; bb′, finer gravel and sand; c, clay (after Rutot and Broeck, p. 57, 346).

but this paper is not available at the present writing. An important contrast may be noted in the arrangement of beds in the normal fresh-water cycle compared with that in the marine cycle. In the latter finer beds are necessarily laid over coarser during the gradual transgression of the sea upon the land, so that a section normally shows coarse sediments at the bottom with finer beds above. Figure 1 displays such a section with some minor interruptions. In the case of lakes, the sediments brought in by rivers tend to encroach upon and fill up their basins so that the coarser materials, which are deposited nearest the shore, advance lakeward with the contraction of the coast line and thus become superposed upon finer materials which were deposited when the former shores were more distant. Such a section would show finer materials overlaid by coarser materials, as illustrated in Figure 3, after Rutot and Broeck.

Estuarine Deposits. Not many accounts of estuarine deposits were found by the writer. Sollas, in a study of the estuaries of the Severn and its tributaries, accounts for the muddiness of the Severn estuary by the ineffectiveness of tidal erosion. He quotes (Sollas, p. 612–613) the experimental results of W. R. Brown, who found that for two-thirds of the ebb, though the surface water runs out rapidly, the water at the bottom is practically at rest; only during the remaining third of the ebb does the bottom water flow outwards with sufficient velocity to scour the channel; this, moreover, lasts so short a time that hardly as much mud and sand are removed as have been laid down during the flood and the earlier part of ebb tide. Hence the sediment is in continual oscillation up and down the estuary (A. Geikie, p. 510–511). Sollas describes the mud, discusses its source and concludes that it is largely marine on account of the organic remains. The mud contains (Sollas, p. 613) argillaceous granules, small angular fragments of quartz containing cavities, a few similar fragments of flint, silicious fragments of a glauconitic color, minute crystals of quartz and tourmaline, together with sponge spicules, and minute organisms. Sections of the alluvial flats (ibid., p. 622) show gravel at the bottom, containing rolled pebbles, angular and subangular blocks of Millstone Grit, and vein quartz. Some blocks are more than one cubic foot in size and one subangular fragment is well smoothed and striated as if by ice. Sands, clays, and peat also occur in the section but the sands (ibid., p. 623) are not a constant feature; they are either marine or tidal and are probably explained by local current action. Sollas does not account for the presence of the gravel.

Willis, discussing the Devonian sediments of Pennsylvania and Maryland, remarks: "The unassorted mingling of sandy and clayey particles is the result of rapid deposition at the mouths of muddy streams in opposition to waves that are too weak to sort and distribute the volume of sediment. This is a condition of delta building. The frequent and irregular interbedding of coarse sands, sandy clays and clays, the cross-stratified beds, the ripple-marked and sun-cracked mud surfaces, the channels scoured by transitory streams, all prove the abundance of sediments, the shifting conditions of deposit, the irregularity of currents, the wide expanse of tide-flats and shallow waters and the weakness of the waves" (Willis, c, p. 63).

Russell (b, p. 46–47) outlines the argument for the estuarine and swamp origin of the Newark system as follows: (1) the absence of marine or fresh-water fossils suggests brackish water and unstable conditions; (2) the fossil fishes are closely allied to the existing ganoids

of rivers and lakes; perhaps they were of migratory habits like the present salmon; (3) the alternations of sediments, which are frequently cross-bedded and preserve foot-print and raindrop impressions, indicate the prevalence of high tides; the presence of land plants in the more carbonaceous portions of the deposit, and of fossil wood in sandstone in many localities indicate the proximity of land. Russell also reports (ibid., p. 33) from the Connecticut valley a coarse conglomerate which sometimes contains rounded boulders two to three feet in diameter and occurs along the eastern margin but is seldom found on the western border. In the southern areas, on the other hand, the Newark rocks have conglomerate exposed on the western border but seldom on the eastern border.

Glacial Deposits. In the attempt to discover the origin of coarse and irregularly deposited materials appeal has often been made to glacial action, sometimes without due regard to the features that might be expected to appear if glaciers were really concerned. It becomes important, therefore, to examine the characteristics of the accumulations of the glacial period and of earlier deposits assigned to glacial origin, in order that true criteria for judgment may be obtained. Neglecting morainic heaps of great boulders and the erratic blocks that are so numerous in certain localities, the discussion will be concerned chiefly with those deposits that either are conglomeratic or resemble conglomerates in some of their characteristics, and with the finer associated sediments.

One of the most important glacial deposits is till. This material has been described by numerous writers. According to J. Geikie (p. 7–15) it is a tough, tenacious, stony clay that has evidently been subjected to great pressure. It often becomes coarser and sandier and in certain districts may be described as a coarse agglomerate of subangular and angular stones set in a scanty matrix of coarse earthy grit and sand. Sometimes the stones are so numerous that hardly any matrix is visible. The stones vary in size from mere grit and pebbles up to blocks several feet or even yards in diameter; the last are less abundant than the smaller materials. Perhaps stones varying from two or three inches to six or eight inches predominate. They are neither round nor oval, like river gravel or sea shingle, nor sharply angular. The sharp edges and corners are smoothed and the stones are scattered in pell-mell confusion. They are smoothed, polished, and striated and have the more pronounced striations parallel to their length. The materials are generally local in character and sometimes there is a rude stratification. When the layers separate, the

surfaces usually show a polished or glazed appearance. If the clay of one stratum be washed and sifted it is found to be composed of grains of all shapes, sizes, and weights down to the most impalpable flour. The till often contains nests, lenticular layers, and occasional thick beds of gravel, grit, sand, and brick clay, frequently curled up and contorted as if rolled over upon themselves along with the clay in which they are inclosed. Though the stones usually are distributed without reference to their relative weight and size, one may occasionally observe within a given area large erratics arranged with their longer axes lying in the same direction. The same thing has been noted with regard to the smaller fragments of grit and clay.

Stone (p. 30) calls attention to the indiscriminate mixture of coarse and fine fragments in the till and adds that the lower layers contain more fine material and a much larger proportion of distinctly scratched or glaciated stones than the upper layers. A. Geikie notes (p. 548–549) that "the detritus is for the most part fresh and angular. Its trituration by the glacier reduces the size of the particles but retains their angular character, so that, as Daubrée has pointed out, the sand that escapes from the end of a glacier appears in sharp, freshly-broken grains and not as rounded, water-worn particles."

A few years ago Crosby made an investigation of the constituents of till taken mostly from the greatest accessible depth in a number of drumlins in the vicinity of Boston. Some of his conclusions are outlined as follows: —

(1) "it is doubtful if stones and boulders more than two inches in diameter often form more than five to ten per cent. of the till and the instances will certainly be very rare and local where they form more than twenty per cent." (Crosby, j, p. 120).

(2) "the normal till of the Boston Basin is composed, after the larger stones are excluded, of about 25 per cent., or one-fourth, of coarse material which may be classed as gravel; about 20 per cent., or one-fifth, of sand; 40–45 per cent. of extremely fine sand or rock-flour, and less than 12 per cent. of clay" (ibid., p. 123). The gravel particles are described as ranging in size from one twelfth of an inch to nearly two inches in diameter, having subangular forms, and tending, when not of exceptionally hard or brittle character, to present flat forms, smooth and often distinctly striated on two or more sides, while the remaining aspects are quite angular or exhibit little wear (ibid., p. 125). The sand consists chiefly of angular quartz grains with fragments of some other minerals. The rock flour is composed of still more nearly pure quartz and even the clay seems to contain impalpable quartz (ibid., p. 127–129).

(3) A comparison of glacial silts with Miocene clays from Gay Head shows that while the former contain a high percentage of rock flour in comparison with clay, the latter are more argillaceous. On the other hand the evidence from the Cretaceous clays of New Jersey is conflicting. While therefore, "glacial silts of every age must be, as a rule, if not always, highly siliceous, the converse is less true," (ibid., p. 136–137).

The pebbles or stones in the boulder-clay are thus described by A. Geikie (p. 1311): "They are usually oblong, have one or more flat sides or 'soles,' are smoothed or polished and have their edges worn round. When they consist of fine-grained, enduring rock, they are almost invariably striated, the striae running on the whole with the long axis of the stone, though one set of scratches may be seen crossing and partially effacing another. . . . These markings are precisely similar to those on the solid rocks beneath the boulder-clay." Similar features are noted by Stone (p. 25).

The so-called "glacial gravels" are, strictly speaking, water-laid deposits, yet they are so intimately associated with glacial action that they may appropriately be treated in this section. They are extensively developed in northwestern Europe and northeastern North America and have formed the basis of a considerable literature, from which a few citations will suffice to give an idea of their general character.

In the discussion of eskers, J. Geikie states (p. 169) that "the steeper ridges are composed chiefly of gravel, generally coarse with little or no trace of bedding. In many places they may consist of tumultuous heaps of coarse gravel, shingle and water-worn boulders or of agglomerates of large blocks and angular and subangular debris mixed with earthy grit and sand. The abrupt embankments on the other hand are usually built of finer gravel and sand and are often beautifully bedded." There is a frequent passage (ibid., p. 170) into true morainic material; large and small angular fragments of rock occur in the heart of the water-worn gravel. The bedding is confused and the stones have a less rounded aspect in the upper part.

Terraces are described by J. Geikie (ibid., p. 175) as deposits not always well water worn. Sometimes indeed they consist only of angular and subangular stones and a kind of earth or earthy sand and clay.

Kames (ibid., p. 183) are usually stratified and in some fine grained accumulations there are beautiful examples of false bedding. In many cases coarser heaps of shingle are piled in confusion without traces of stratification. It is remarkable that the gravel stones whether

small or large are almost invariably well rounded and water worn. In the occasional exceptions the deposits are not only unstratified but earthy, and the stones angular and subangular, some even showing faint ice-markings. Such deposits are associated (ibid., p. 184) with heaps of well-worn sand and gravel, showing that they belong to the same series. Clays are sometimes associated with the sand and gravel but there are no organic remains in either.

Speaking of the shapes of drift fragments, Stone remarks (p. 40) that in glacial gravels we find all degrees of water wear. Most of the stones and grains found in kames and osars show a very large amount of attrition and rolling and are very much rounded.

The intimate relation of till and glacial gravels is shown by Penck (p. 132):— the till with angular, striated boulders overlies and is interbedded with coarse gravel, sand, and clay, both horizontally bedded and showing false stratification. He cites (ibid., p. 137) the observations of several writers to the effect that striated pebbles soon lose their glacial markings when subjected to the action of water.

One of the most characteristic features of glacial regions is the effect of the ice movement on the underlying rocks, which frequently acquire a smoothed and often highly polished appearance. The whole surface is marked with striae, especially the close grained rocks, such as limestone. Sandstone and highly jointed rocks are usually much less marked and often show a broken and shattered surface below the till (J. Geikie, p. 18–19).

Another feature of glacial action is to be noted in regions where glaciers descend to sea level, or enter large lakes. The icebergs that float away from the end of the glacier are more or less charged with debris, embedded within their mass. As they melt, the morainic material is dropped upon the bottom of the lake or the sea. It may often happen, therefore, that coarse, angular material, bearing glacial markings, may be dropped among the finer sediments at some distance from shore and may thus become embedded in a well-stratified, argillaceous matrix, in which may also be contained the remains of marine or lacustrine organisms. Stranded icebergs produce local contortions and interruptions in the bedded deposits on which they rest.

Sea ice frozen to the shores may bear away great quantities of loose debris, when the floes break up and are driven away by the wind. Tarr, sailing for a thousand miles along the American coast north of the straits of Belle Isle, much of the time among ice-floes, estimated that about one per cent of the cakes carried debris of some kind, while in some cases ice cakes were black with it (A. Geikie, p. 578). Similar

phenomena may occur in lakes under favorable conditions. River ice may also inclose more or less coarse stony waste, which the streams may deposit along their courses or may bear away to some lake or to the ocean. Again, trees, uprooted and borne along by floods or undermined by wave action at the base of cliffs that they surmount, may embrace among their roots large fragments of rock, which may thus be floated away and deposited among finer sediments. Moreover, the masses thus transported and deposited may already have been marked with striations, due to the jamming of ice cakes either along shores or against river banks.

The mere occurrence, therefore, of striated boulders among fine bedded lacustrine or marine sediments cannot be regarded as indubitable evidence of glacial action. The relative number and shape of the fragments and the character of the striations must be considered. In the case of fragments distributed by icebergs, the shape is generally that of pebbles embedded in boulder-clay — faceted, with snubbed ends and rounded edges — and the striations are commonly more strongly marked parallel to the length of the fragment, though two or more directions may be indicated on the same stone. Occasional larger masses not so shaped and striated might occur, for it is possible that an iceberg might carry some masses that had fallen on the surface of the glacier and had not been subjected to movement under the pressure of superincumbent ice. In the case of debris distributed by shore or river ice the shape of the fragments would generally be that of beach shingle or of stream pebbles — rounded or subangular — and the striations would not so commonly be in the direction of the long axis of the pebble. Here again, larger or more angular masses might occasionally appear, for fragments freshly broken from the parent rocks might be embedded in ice and floated away before they were shaped by water action. In the case of materials distributed by floating trees the same comments as to shape and striations would apply as in the case of shore or river ice-rafted waste. The number of fragments thus distributed is, however, probably much less than that disposed of by any of the above noted methods.

Deposits assigned to glacial action in ancient periods occur in a number of countries. These will now be described in order to obtain the criteria by which their glacial origin was determined.

——:—*India.* At the base of the Gondwana system and resting unconformably on older Palaeozoic rocks there is a group of peculiar sediments discovered in 1856 by W. T. and H. F. Blanford and named by them the Talchir group. These rocks have been described by

Medlicott and W. T. Blanford, R. D. Oldham, C. D. White, and others. The main characteristics as summarized by White (p. 302–303) are quoted in substance as follows:—The Talchir boulder beds underlie coal-bearing strata, are often 500–800 feet thick and consist of clays, fine silts, boulders, sandy shales, conglomerates, and soft sandstones. They are distinguished everywhere by semi-angular and somewhat rounded pebbles, boulders and rock masses of quartzite, Vindhyan rocks, granite, gneiss, and metamorphics. The boulders are usually foreign to the localities where found, are generally but slightly rounded and are smoothed, furrowed, and striated in parallel straight lines. Often the boulders are faceted, perfectly polished and striated in two or more directions, similar to fragments shaped and marked by glaciers. The boulders are not at the angles of repose incident to current action, but lie at all angles, embedded in silt too fine to admit other explanation than the action of floating ice. In the neighborhood of Madras quartzite boulders with a volume of 800–1,000 cubic feet occur in a matrix of friable clay. At another locality a mass of rock $10 \times 7\frac{1}{2} \times 3$ feet is found which is similar to no rock nearer than the Arvali Mountains, 150 miles south.

This description may be supplemented by a few additional details taken from the accounts of R. D. Oldham. The matrix of the boulder-bed is described (b, p. 468) as "always tolerably and often extremely fine grained. . . . itself distinctly stratified and interstratified with well-bedded rock. Through this are scattered blocks of all sizes, always embedded in and well separated by the matrix. Where finely laminated, the bedding is observed to bend down under and arch over the included fragments. The matrix was deposited in quiet water. Driftwood and volcanic agency are excluded; the only adequate explanation is floating ice. Many boulders are striated and in two localities the beds rest on a striated *roche-moutonnée* surface." The soft sandstones accompanying the Talchir group contain undecomposed feldspar (ibid., a, p. 157).

Glacial boulder-beds of corresponding age have been described from several rather widely separated localities in India and similar rocks have been reported from Kashmir (ibid., a, p. 135). It seems therefore that the glacial formation extends over a wide area in that region.

——:—*Australia.* Boulder-beds similar to those of India occur in New South Wales. "Large boulders of foreign rock with distinctly glacial smoothings and striations occur, embedded in fine grained silt along with delicate Fenestellae and bivalves whose valves are still united

in the position in which they lived and died" (Oldham, a, p. 121). The deposits of several localities are described by David, who, in addition to his own observations, gives a bibliography of the subject. At Hallet's Cove near Adelaide the boulder-beds rest on a striated pavement on which the striae run from north to south. The glacial beds consist of reddish brown clay slates, sandy in places and fairly well stratified, especially in the upper part. Downward they pass into sandy grayish brown sandstones, containing well-striated boulders in abundance. The latter are distributed only sparingly in the upper part of the deposit. The boulders range in size up to masses of eight tons' weight and have a possible source thirty-five miles south. The thickness of the boulder-beds ranges from twenty-three to one hundred feet. There are no traces of organisms in the matrix, which is local in character (David, p. 294). At Wild Duck Creek, Victoria, the striated pavement is again noted. The glacial beds consist of mudstones, with erratics reaching the size of thirty tons, and sandstones. Nearly all the erratics and small boulders are beautifully polished and faceted. The formation has been traced over an area fifteen and one-half miles long and five miles wide. Its thickness varies from 300 to 400 feet and the materials appear to be derived from a southerly source (ibid., p. 295).

The Bacchus Marsh Beds in Victoria also rest on a striated pavement with uneven surface. They consist of mudstones, conglomerate, and sandstones. The mudstones are hard and soft, varying in color, with a small proportion of fragments of undecomposed feldspar, minute chips of black shale and small pieces of carbonized plants. The soft mudstones consist of clayey material with quartz grains, mostly subangular, and contain sparingly glacial erratics. The hard mudstones contain numerous firmly embedded erratics that are frequently flattened and have diameters up to five and one-half feet in length, though the fragments are usually less than one foot long. The maximum thickness of individual beds is 193 feet (ibid., p. 296). The conglomerates are composed of well-rolled pebbles one to six inches in diameter. They have an irregular under surface because they rest upon the irregularities of the lower beds. The maximum thickness of individual beds is twenty feet. The sandstones are hard and soft, coarse and fine, frequently laminated, and occasionally showing distortion, especially in the neighborhood of irregular pockets of conglomerate. There are well-preserved plant remains in the last two horizons. The thickness of the individual beds is thirty to one hundred feet. The thickness of the entire series, according to the

later determinations, is 1,427 feet (ibid., p. 297). The extent of the glaciated area in Australia is from latitude 42° S in Tasmania to 26° 31′ S in Queensland and from 137° 30′ E longitude to 151° 31′ E longitude (ibid., p. 300).

——: — *South Africa.* A considerable literature has already appeared with reference to the nature and origin of the Dwyka Conglomerate, which forms the base of the Karoo system and overlies unconformably sandstones and shales that have Devonian affinities. The most recent publications that have come within the notice of the writer are by Mellor, Rogers, and Emmons. The last gives a general summary of the literature up to 1896. As described by Rogers, the rock is usually bluish or green, compact and fine grained, composed of quartz and microcline, with a small quantity of other feldspars, epidote, garnet, calcite, and other minerals embedded in mud (A. W. Rogers, p. 147). The mud contains a vast number of boulders and pebbles of a great variety of rocks, scattered irregularly through the conglomerate without any arrangement in beds. There are many rounded boulders but there are also many flattened on one or more sides, with scratches of various depths, generally in two or more directions (ibid., p. 142). In all respects these boulders and pebbles are similar in form and in the nature of striation to those found among the glacial formations of northern Europe and America (ibid., p. 150). Some pebbles attain a diameter of ten feet (ibid., p. 167).

The upper portions of the formation (Mellor, p. 685) are "locally associated with beds of massive sandstone and lenticular patches of cream colored shales and mudstones, which appear to have been deposited in pockets in the conglomerate and to consist of the finest glacial mud. The laminae are readily separable; they are smooth and similar in appearance and color to lithographic limestone or they are covered with delicate ripple-marks, as many as forty in the space of one inch." The underlying surface gives clear evidence of the direction of ice movement, from north southwards. The striae maintain a constant direction over large areas (ibid., p. 688). From the statements of Molengraaf and Rogers it would appear that the stratified portions of the conglomerate are not so local in their occurrence as is perhaps implied in Mellor's description. Molengraaf speaks (p. 260) of the unstratified mass as alternating with stratified beds which sometimes contain many boulders and pebbles. Rogers states (p. 154) that it is justifiable to regard those portions of the conglomerate that rest upon a striated floor as terminal or ground moraines, but that it is uncertain whether the whole of the conglomerate in the region

was formed under quite the same conditions. He thinks (ibid., p. 153) that boulders and pebbles as well as some components of the matrix of the conglomerate reached their present positions by means of icebergs and drifting floes.

The microscopic characteristics of the ancient boulder-clay are mentioned by Molengraaf and Green. The former states (p. 260) that the mud contains numerous small angular fragments of different rocks and minerals, chiefly quartz, and that the clastic structure is modified by recrystallization, which gives the rock a strong resemblance to volcanic tuff or breccia. Green (p. 242) notes the markedly angular and varied shape of the fragments. He states that they are nearly all limpid quartz containing fluid cavities; "the fractured nature of the quartz grains comes out beautifully under moderately high power, but often other parts of the edge in the same grain are smoothed and softened off as if by the action of some solvent." The writer has examined a slide made from a specimen of the Dwyka conglomerate kindly placed at his disposal by Professor Davis. In addition to the characteristics already noted the following features were observed. Several minerals besides quartz were present, including among others microcline, plagioclase, garnet, and biotite. The feldspar fragments showed little or no kaolinization and the mica flakes were frayed at the ends.

The glacial boulder-beds of the Dwyka Conglomerate are not, strictly speaking, conglomerates, according to the definition given above (page 107). They are really such rocks as would be formed by the consolidation of masses of boulder-clay or till of the last glacial epoch. The name "tillite," suggested by Penck during a recent visit to the South African field is more definite and distinctive.

An important and characteristic structure, since shown to be secondary, is described by Green. He says (p. 242) that "in many places no bedding is discernible, but where the rock is exposed it has a bedded look, parallel bands making their appearance on the weathered face, differing from one another in color, and some weather faster than others. Slabs resembling rudely shaped tombstones stand in parallel rows along the hillside." The thickness of the formation is 500–800 feet (C. D., White, p. 306).

——:—*Correlation; India, Australia, South Africa.* It appears that similar beds of glacial boulder-clay have been found in India, Australia, and South Africa. The general belief that they were contemporaneous is well summed up by Oldham. He says (a, p. 206), "In Africa, India and Australia alike, certain beds contain abundant

and conspicuous traces of glacial action. Plant remains show that in South Africa, the Indian Peninsula and Victoria these are of approximately the same age, and marine fossils show the same with regard to the beds of New South Wales and the Salt Range. The deposits in every case were formed during a period of great cold, which was succeeded by a much more temperate climate and it is almost impossible to doubt that this wide-spread change of climate must have been due to some far-reaching, if not cosmic, cause. Consequently it is justifiable to use the glacial deposits for the purposes of correlation and to conclude that the boulder beds of the three continents were formed contemporaneously."

——:—*England*. The conglomerate or breccia in the Upper Old Red Sandstone of England was believed by Ramsey to be of glacial origin. It has already been shown that the rocks in question are more locally derived than Ramsey thought and that they are in all probability of fluviatile origin. Nevertheless it is interesting to note the facts that led him to advocate the glacial idea. The arguments may be stated under four heads:— (1) Many of the fragments are of great size; the largest observed weigh one-half to three-fourths of a ton; (2) rounded fragments are exceedingly rare; the fragments are angular and subangular and have the flattened sides so characteristic of many of the glacial fragments of existing moraines; (3) many are highly polished and others are grooved and finely striated like the stones of existing glaciers; (4) the hardened cement, marl, may be compared to boulder-clay.

——:—*Norway*. At the head of the Varanger Fiord in northeastern Norway are some ancient glacial deposits, discovered and described by Reusch and later visited and commented upon by Strahan. According to the latter (p. 140 et seq.), the thickness of the formation nowhere exceeds ten feet. The base is remarkably straight but the upper surface undulates and the overlying sandstone is deposited tranquilly upon it in such a way as to level up the irregularities. For an inch or two at the base the overlying sandstone contains material washed up from its surface. The formation itself is described as a "dark bluish or ashy gray, friable rock, composed of a heterogeneous mixture of grit, sand and clay, of all degrees of coarseness and containing boulders ranging up to two feet in length scattered through it. Though quite unstratified, it shows here and there a slight schistose structure" (merely an obscure fissile structure is meant in consequence of which the rock splits more easily than in other directions; the microscope shows no crushing). "The included boulders, which are all shapes

and lie at all angles, consist principally of red and gray granites and quartz-grits resembling those of the Gaisa formation." No striated blocks were seen but on account of the hardness of the adhering matrix Strahan had time to examine only two or three specimens. "The boulder rock rests on regular bedded sandstone of the usual type and weathered back so as to expose several square yards of a remarkably even surface of rock. The platform is not only smoothed but conspicuously and characteristically striated and the striae can be followed under the boulder rock. The striae unquestionably cut into the rock independently of any structure possessed by the latter and are in all respects glacial markings." The age of these rocks is uncertain. They may be Cambrian or older or as late as the Triassic. "In general lithological character they belong to the type of great continental formations."

In southwestern Norway, on the islands and peninsulas near the Sogne Fiord, there are some conglomerates that have been made the object of a special study by Helland, whose paper was kindly translated for the writer by Mr. B. Palsson. This formation varies in thickness from 1,000 to 6,000 feet and is distributed in four entirely separate districts, which have a total area of 1,140 square kilometers. The conglomerates rest (Helland, p. 25) on slates in open synclines which are tilted westward. The southern district consists entirely of conglomerate, the northernmost of sandstone and the intermediate districts of both conglomerate and sandstone. The pebbles are of many kinds of material and are sometimes so angular that the formation is almost a breccia. The size and character of the pebbles and the characteristics of the matrix are variable in the different districts and in the same district (ibid., p. 30). The materials vary in size from microscopic particles to masses over 1.5 meters in length and a little over a meter in breadth (ibid., p. 35). The conglomerate is not stratified. Pebbles of the same size are seldom together; on the contrary, materials of different size, character and specific gravity lie side by side (ibid., p. 38). The matrix (ibid., p. 45 et seq.) is either slaty or silicious and is variable in quality and abundance. In some places there is very little of it while in others it constitutes about one-third of the rock. The slaty matrix consists of clastic fragments of quartz, feldspar, and other minerals, together with a fine paste of amorphous matter containing some greenish crystalline needles. In the silicious matrix the clastic fragments are larger and much more conspicuous and the paste appears only as a little rim around the fragments. The paste, however, has crystallized and contains chloritic minerals and

epidote. The age of the conglomerate is not known because no fossils have been discovered in it (ibid., p. 62).

As regards the origin of the conglomerate Helland argues (ibid., p. 63 et seq.) that the rock was deposited in separate synclinal basins and that the materials of which it is composed were derived from the surrounding mountains. In the discussion of their possible means of transportation he recalls the variety in substance and size of the pebbles, their unsorted and heterogeneous arrangement and their shape, which is rounded but nothing like the form assumed by beach pebbles (ibid., p. 70). Their formation as waste accumulated at the base of mountain slopes is considered unlikely because the pebbles in the conglomerate are not angular, the heaviest masses do not lie farthest down and the materials of which they are composed are not similar (ibid., p. 71). Fluviatile or lacustrine origin may be assumed for the more sandy parts of the formation, for the deposited masses in a lake are usually more or less plainly divided into layers of sand and stones arranged according to the varying action of the currents; moreover, the pebbles rest on their surfaces that are nearest flat and the largest ones are deposited at the mouths of the rivers (ibid., 72–73). But a large part of the formation, including even one entire district, the Sulen Islands, is filled with pebbles that are not in the least like alluvial formations. On the contrary, they are most like the diluvial formations of the north European plain (ibid., p. 74). The lack of striated pebbles, the most prominent peculiarity of glacial formations, is important, but this fact does not exclude the possibility of glacial origin, for it is often difficult to find striated pebbles in accumulations that are admittedly glacial. It must be remembered, too, that where the conglomerate is most like the diluvial masses the matrix is firm and fine grained so that the pebbles are more easily broken than removed, and their surfaces are seldom seen. When the matrix is sandy the conglomerate is more like the German "Diluvialkies" which usually has no striated pebbles (ibid., p. 75). Helland's conclusion therefore is that the combined activity of ice, water, glaciers, and rivers seems to be best adapted for the production of such a varied formation as the conglomerate in question (ibid., p. 80).

——:—*Alps.* Along the northern base of the Alps extensive masses of conglomerate occur, the so-called "Schotter Conglomerates," which are intimately associated with glacial deposits. Those in the Salzach region of Austria and Germany are described by Brückner. At Emetsham, at Hohenwart on the Alz and at Handenberg, the Schotter

deposits begin just at the borders of the outer moraines and slope away from the latter like alluvial cones (Brückner, a, p. 74). "South of Schutzing on the Engelbach . . . . the high terrace Schotter carry great blocks and at the same time mud and striated boulders. The deposit could be counted as part of the outer moraines if the bedding and external form as a terrace did not make evident its character as high terrace gravel." At Traunstein the high terrace gravel constitutes the perpendicular bank of the Traun; the upper layers here form several alternations of deposit with the moraines (ibid., p. 75).

——:—*Iceland.* In the past few years evidences of several successive glaciations that preceded the final glaciation of Iceland have been discovered by Pjetursson, who has written several papers on the subject. Some of these evidences are discussed in a paper by H. G. Ferguson, who recently visited the region with Pjetursson. For the present purpose it will suffice to give a brief account of the phenomena as they were described by Pjetursson after his first discovery. In the mountains overlooking the southern lowlands of Iceland the so-called "Palagonite Breccias," of which they are in part composed, present a striking resemblance to a very stony boulder-clay (Pjetursson, a, 267). The hard sandy matrix is crowded with a great number of blocks of basalt, mostly subangular and ranging in size up to three or four feet. Many of the stones are distinctly striated and cannot be distinguished in that respect from striated stones in loose glacial accumulations. The matrix is hard and well jointed, the steep escarpment being determined by a joint plane. Thin lenticular layers of fine grained, distinctly stratified material are intercalated in the breccias, especially in the lower part (ibid., p. 268). The mass of the breccia shows a commingling of material of every size of grain from fine clay to large sized blocks. Part of the latter are angular, more are blunted, some are striated. Minor quantities of fine grained stratified material are intercalated with the unstratified deposit and the bedding is often diagonal. Some of the breccias rest upon distinctly striated and grooved rock surfaces (ibid., p. 269).

——:—*United States; Newark Formation.* In the Triassic rocks of the eastern United States coarse conglomerates and breccias are found at many localities. These occurrences have caused some speculation as to the possibility of glacial action in connection with their deposition. Russell shows (b, p. 50–51) that the evidence is insufficient to support the hypothesis of glacial action in these cases and in that connection he gives a list (ibid., p. 49–50) of direct evidences of glaciation which one might expect to find preserved. This list is pertinent to the present inquiry and is therefore given:—

(1) Smooth and striated rock surfaces or casts of the same.
(2) Boulders, smooth and striated and faceted by the glacier.
(3) Morainal material in irregular and unassorted heaps.
(4) Ice-rafted boulders in the fine sediments of deep water.
(5) The flora is not conclusive since forests grow close to existing glaciers and even cover portions of the moraines on their surfaces. In the animal remains associated with fine deposits we should expect the best records of climatic conditions.

——: — *South America.* The earlier work of Agassiz and Hartt in Brazil led them to believe that there also glacial action had taken place. An account is given by Branner of their earlier views and later changes of opinion, together with a statement of the facts on which the earlier ideas were based, and their true explanation. Large rounded boulders, sometimes striated, and supposed to be erratics, were often found embedded in what was considered boulder clay. Moreover there was found a widely distributed accumulation of transported, water-worn materials, which were believed to be of glacial origin (Branner, p. 759). The so-called erratics are shown by Branner to be boulders of decomposition, either rounded or subangular, embedded in residual and consequently unstratified clays. Soil-creep and landslides tend to obscure the true nature of the deposit and the landslides have sometimes caused well-marked striation and faceting (ibid., p. 761). The water-worn materials are shown to be reworked Tertiary deposits in which the finer sediments have been washed out and the coarser debris left behind by wave action permitted by a Posttertiary depression of the land (ibid., p. 768).

Traces of a Carboniferous glaciation in South America are reported by Derby, who notes a resemblance in the characteristics of fossils between the Carboniferous formations of southern Brazil and those of Australia, India, and South Africa. In the South American rocks Derby observed rounded boulders from the size of the fist up to four times the size of the head, lying in clay slate and projecting from it. In one place he found blocks of various rocks, such as granite and gneiss, lying in a stream bed among clay slates. The assemblage of such large masses of different materials and the fact that the clay slates of the stream banks in the immediate neighborhood contained an abundance of smaller blocks convinced him that the boulders had been transported. The manner of their occurrence appeared to exclude the action of streams or waves, but no striated surfaces had then been found on any of the blocks (Derby, p. 175).

The resemblance of the South American rocks to those of India is

further noted by Kurtz, who has found in certain beds exposed in the Argentine Republic a number of fossils which show them to be allied to the lower Gondwana rocks of India (Kurtz, p. 111 et seq.).

Crush-Conglomerates. "Where rocks lie under too light a load to become plastic, and have, therefore, given way to great crushing by breaking to pieces, their broken fragments may be pushed along shear planes or in fault zones, and may thus be pressed against each other and rolled forward, until their edges are rounded off and they acquire much resemblance in general form to the pebbles of a conglomerate. Bands of such comminuted materials are of not infrequent occurrence among Palaeozoic and older formations which have suffered much disturbance. They are known as Crush-conglomerates, or, when the fragments are angular, as Crush-breccias" (A. Geikie, p. 683). Rocks of this character in the Isle of Man are described by Lamplugh, who notes the gradual smashing into fragments of highly contorted strata until every trace of the original bedding is lost and a crush-conglomerate with lenticular and partly rounded inclusions is formed (Lamplugh, p. 372–373). A similar instance in Argyllshire is described by J. B. Hill. Limestones with epidiorite sills have been intensely folded and isoclined (J. B. Hill, p. 313 et seq.). The epidiorite has been fractured and in some instances rounded so that the appearance is that of boulders in a limestone matrix. Fragments of the epidiorite (ibid., p. 324) may be seen here and there enclosed in the main mass, as well as the remains of crests and limbs of folds that have been torn from their original position and formed into augen-structures.

Combinations of Processes. It is evident that conglomerates may be formed as the result of the action of two or more of the processes already mentioned. For example, the glacial deposits which are so abundant in New England are in many places being worked over by the sea. The angular and subangular striated pebbles of the till are being rounded and sorted by wave action in many places along the present beaches. The mill of the sea quickly removes the glacial markings and the rounded pebbles soon produced cannot in themselves be distinguished from those formed by marine action alone. It is only when the modified deposits can be seen in proximity to unmodified portions of the mass from which they were derived that their originally glacial character can be assumed with confidence.

In the Champlain valley extensive lakes, dammed by the retreating ice sheet, and the later invasion of the sea itself have produced a number of shore lines at different levels, which have recently been described in some detail by Professor Woodworth. Beaches have been formed

of material worked over from the till sheet that once covered the region. At one locality a morainal ridge (Woodworth, e, p. 34) is composed altogether of blocks and cobbles of Potsdam sandstone. On the crest and western or landward side the blocks are still prevailingly angular. On the eastern or wave-washed slope the blocks are often well rounded, particularly at the lower levels. "The fragments decrease in size from the crest and near the 600 foot level are coarse gravels. The large blocks are between three and four feet in length, but blocks yet longer occur. Ovoid masses of this size in the upper zone of beach action attest the strength of the waves." At a second locality, a low, modified hill about two miles northwest of Mooers Junction, rolled and rounded pebbles appear on the west slope. "The underlying glacial materials are the angular rock fragments peculiar to glacial till. It is evident that long continued and effective wave action took place on the west slope of this hill" (ibid., p. 40–41). The rounding of the glacial fragments in these shore lines, together with the sorting of the materials at the first locality indicate the character of the changes produced by either lacustrine or marine wave action upon unsorted glacial debris. The longer such processes are continued the more perfect become the shaping and sorting of the materials, until all traces of glacial action are removed. In the Champlain valley the lacustrine and marine stages at which the shore lines were built must have been of relatively short duration, for not only are the glacial deposits only slightly modified but in some instances the beaches are seen to rest on glaciated surfaces (ibid., p. 33).

The intimate association of fluviatile action with glacial action has already been noted. The materials swept from a glacier by torrents of ice water soon lose their distinctive shape and markings unless deposited before they travel far. The ordinary stream washed glacial materials along the northern side of the Alps are described by Penck (Penck et al., p. 8) as worn, rolled, rounded, and deposited like the pebbles of a water course. They are characterized, he says, by their horizontal stratification or by an alternation of horizontal and inclined layers. Upstream the alluvial deposits become larger and more angular, the stratification becomes less regular, striated pebbles appear and the formation becomes truly glacial. Between the unmodified glacial material and the undoubted "fluvio-glacial" deposits is a transition zone characterized by a morainic phase of the alluvium, and by the presence of blocks or of occasional striated pebbles. The "fluvio-glacial" material rests against the actual glacial debris, and forms a vast inclined plane descending from the moraines and forming

a low cone. Down valley the cone becomes more flat as the internal structure becomes more regularly stratified. This is the fluvio-glacial region proper. The transition cone often presents alternations of glacial and fluvio-glacial material, which may appear at the base, within the mass or near the surface of the alluvium (ibid., p. 9).

From these examples it will be seen that there is considerable similarity in the shape and character of some of the individual particles and masses produced by each process. The effects produced by one process alone may differ in a notable degree from those produced by another, but when they are combined, a gradation occurs, so that no sharp line of distinction can be drawn; and it is difficult or impossible to determine to which of the processes some of the materials deposited should be assigned. Accumulations produced by such combinations of processes are probably more common than those formed by the separate action of a single process. River-borne waste is rehandled by the sea. Even in the formation of what might be called truly glacial material washed gravels are apt to be interstratified to some extent with the till in consequence of the minor variations in the position of the ice front. Recognizing, then, the fact that many combinations are both possible and probable, it is best for the purposes of this paper to confine the discussion to those features which may serve to identify the several processes.

Analytical Discussion.—In the previous pages the details of various occurrences of conglomerates and associated rocks have been set forth at some length, together with the opinions of numerous writers concerning some of the characteristics of conglomerates formed by the different processes. It now remains to gather from this material the typical features of each kind of conglomerate and to arrange them in some order for comparison. For this purpose the following scheme has been adopted:—

Matrix:— kind of material; size of grains (coarse or fine, uniform or varied); shape of grains (angular, subangular, or rounded); arrangement of grains (orderly or disorderly; well stratified, rudely stratified, or unstratified); cement (argillaceous, silicious, calcareous, or ferruginous).

Pebbles:— kind of material; size of pebbles (large or small, uniform or varied, gradation in any particular direction); shape of pebbles (angular, subangular, or rounded); markings (facets, polish, striation); deformation (distortion, tension cracks, fracture); arrangement (well stratified, rudely stratified, unstratified).

Color: — general tone of the rock; relations to matrix; relations to pebbles.

Characteristics of Bedding: — uniform series grading into finer beds, thickness and extent; variable series (lenses of coarser and finer materials, false-bedding, and local unconformities, ripple-markings, sun-cracks, raindrop impressions, or organic markings), thickness and extent.

Relations to Subjacent Rocks: — conformable: nature of the underlying series; unconformable: eroded surface deeply disintegrated, eroded surface of relatively fresh rock unglaciated, eroded surface of relatively fresh rock glaciated.

Under each of the major headings of the scheme each kind of conglomerate will be considered briefly, with reference to the minor headings, as the data will permit.

Matrix: — *Marine.* In the Texas example of marine conglomerate the matrix is described as ferruginous, gritty sand. Stratification is only indirectly implied. In the Pottsville conglomerate where the transition to the underlying Mauch Chunk shales occurs, the matrix consists of coarse arkose sands. For a long distance above the base it is composed of micaceous, chiefly arenaceous material, poorly cemented and often containing some argillaceous coloring matter. Near the upper part of the section coarse gray sand forms the matrix. Both composition and assortment are variable near the base but more uniform near the top. These characteristics tend to ally the Pottsville more closely with fluviatile than with marine deposits, as already noted.

——: — *Fluviatile.* The foregoing citations do not furnish much explicit data with reference to the composition and character of the matrices of fluviatile conglomerates, but in the descriptions of the extensive accumulations of southern Asia and the western part of the United States it is shown that the pebbles of the conglomerates rest in a matrix composed of materials of varying nature and size, which are often only imperfectly sorted and stratified.

——: — *Lacustrine.* No specific data with reference to the matrices of lacustrine conglomerates have been found.

——: — *Estuarine.* In the case of estuarine conglomerates also little direct information was obtained. From Willis's account of the characteristics of the Devonian sediments it would appear that an unassorted mixture of sandy and clayey particles may be expected to constitute the matrix of estuarine conglomerates. This expectation is verified in the account of the tidal flats of the Severn, given by Sollas.

——:—*Glacial.* The till of the Glacial period, as described by J. Geikie and by Crosby, excluding the embedded stones, consists of tough stony clay, composed of grains of all shapes and sizes down to impalpable flour; or, when the matrix is more scanty, of coarse earthy grit and sand. The matrix as a whole is highly silicious, containing as much as 60 to 65 per cent of sand and rock flour in addition to coarser, quartzose material.

The matrix of fluvio-glacial conglomerates, as described by J. Geikie and by Penck, varies from true boulder clay to well water-worn sand and gravel; its characteristics are not otherwise described.

Ice-rafted boulders may be dropped into a matrix of well-stratified argillaceous sediments containing marine or fresh-water organisms. This seems to have been the case with the boulder-beds of India and New South Wales, though the latter are described as sandy in places, and containing a small proportion of fragments of undecomposed feldspar, minute chips of black shale and small pieces of carbonized plants. The matrices of the glacial conglomerates in South Africa, Norway, and Iceland appear to be more like the boulder-clay of the last glacial period, since they consist of fine mud, grit, and sand, containing angular fragments of quartz and other minerals, without any definite arrangement.

——:—*Crush.* In crush-conglomerates the materials of the matrix would vary with the rocks involved in the movement and the size of the particles with the intensity of the crushing forces. No data with reference to the general character of such a matrix are at hand but it is probable that the component particles would be angular, unsorted and of varying size.

Pebbles:—Marine. The instances cited show that the pebbles of marine conglomerates are usually composed of the more durable materials though they often vary locally with the nature of the adjacent rocks. As regards size, the pebbles may be either coarse or fine, but there is a tendency within certain limits toward a fair degree of uniformity. There is gradation upward to finer sediments, in the case of the transgressing shore line, and horizontally in the direction in which the conglomerate wedges out. The pebbles are uniformly well rounded except where they are in relatively close proximity to the sources from which they were derived. Cross-bedding frequently occurs. It may be noted, however, that the Pottsville, which, in its upper portions at least, has been described as a round-pebble conglomerate, becomes more irregular in its lower portions, where it sometimes forms poorly assorted or even unassorted pebble or boulder

accumulations. Here again its questionable character as a marine conglomerate is displayed.

——:—*Fluviatile.* The materials of which the pebbles of fluviatile conglomerates are composed appear to vary largely with the kinds of rock exposed within the drainage areas of the streams and are to a considerable extent local in character. In the case of the larger rivers the material has usually been carried farther and has been taken from hard rocks. The pebbles at any given locality may vary in size from fragments hardly larger than grains of sand to masses several feet in diameter. The component masses of the conglomerate diminish in size in the direction of the grade of the stream that deposited them and laterally too they grow smaller away from the larger streams. In the portions of the deposit near the source of supply, the growth of the accumulations causes the coarser material to advance and overlie finer, previously formed detritus, so that coarse conglomerates appear above finer sediments. Farther away from the source of supply deep borings have been made in fluviatile deposits without showing any notable increase or decrease in coarseness of material. As to shape, the pebbles are variously described as rounded, subangular, and 'unrounded.' In some regions they become nearly, if not quite, angular, while in others they approach rotundity. There is thus a lack of uniformity in shape as well as in size. In some cases they are described as horizontally or obliquely bedded, but in others it is stated that they lie with their long axes at all angles with the horizontal plane and without any definite arrangement.

——:—*Lacustrine.* No satisfactory evidence has been found by which pebbles formed by lacustrine processes can be distinguished from those of other origin. Since the littoral processes of lakes so closely resemble those of oceans it is reasonable to believe that lacustrine pebbles will resemble more closely those of marine origin than any other type. We may expect, therefore, that on the whole lacustrine pebbles will be well rounded, but, on account of the absence of tides, they may not be so well sorted nor show such general uniformity of size at any given locality as is true of marine pebbles.

——:—*Estuarine.* The data presented under the head of estuarine deposits show that wave action in estuaries is relatively weak. The coarser material from streams and other sources is therefore subjected to little attrition from this cause and is only slowly modified in shape. As a result the pebbles may be rolled, subangular, or even angular in form. They will, however, tend to be arranged in irregular and cross-stratified deposits by shifting and transitory currents.

——:—*Glacial.* The materials of which glacial pebbles are composed are largely local but there may be a considerable percentage of stones that have traveled great distances. In the main the transported fragments consist of durable rock but sometimes large blocks of weaker material are carried far from their parent rock without being comminuted by ice action. The size of glacial boulders or pebbles may vary from tiny fragments to ponderous erratic masses, weighing many tons. The latter, however, have been transported chiefly on the surface of the ice and have not been subjected to the grinding and crushing suffered by those fragments which have been pushed along over the surface beneath superincumbent ice. As a consequence there is generally a gradation in size in the pebbles of a glacial accumulation, the upper portions as a rule consisting of coarser materials. In shape glacial boulders are usually angular or subangular, and those which have been transported beneath the ice have one or more flat sides, rounded edges, and more or less snubbed ends. Perhaps the most distinctive feature of glacial pebbles is the beautiful polish and striation which the more fine grained and durable fragments receive, the markings running, on the whole, parallel to the long axis of the stone. When these materials are rehandled by intra- or extra-glacial waters or by the sea, the glacial markings are soon lost and the shapes of the pebbles become similar to those produced by fluviatile or other aqueous agency.

Another striking characteristic of glacial accumulations is the marked disorder of their component fragments. Masses of all sizes and shapes are huddled together in indiscriminate confusion. Sometimes, however, there are included masses or pockets of stratified material, and in the reworked glacial deposits all stages of order are represented from complete heterogeneity to well-marked stratification.

——:—*Crush.* The pebbles of crush-conglomerates vary with the nature of the rocks involved in the crushing. No data with reference to size are at hand but it is probable that there is considerable variation. The shape is described as rounded or lenticular, sometimes showing the remains of crests or limbs of folds that have been formed into augen-structures.

Color:—Marine. In the accounts of marine deposits above cited the conglomerates are mentioned as having a ferruginous matrix, and again as being interbedded with red and blue clay. In the case of the Pottsville, the lower portion is described as variable in color, bands of conglomerate alternating with washes of purple and olive mud or soft greenish sandstone. The upper portion, however, is light

colored, dense, and arenaceous. That iron coloration is wide-spread in marine accumulations is attested by the remarkable bed of "fossil ore" in the Clinton group, which extends from New York to Alabama, and by the reddish facies displayed by the Potsdam and Medina sandstones. These colors, however, are not ordinarily intense. In the rocks where the coloration is present it seems to reside in the matrix and is not described as encrusting or discoloring the pebbles.

——:—*Fluviatile.* The data at hand do not supply much evidence with relation to the color of fluviatile deposits. In the Siwalik deposits of India and in the New and Old Red Sandstone of England red colors are present.

——:—*Lacustrine.* No evidence with reference to the color of lacustrine sediments has been noted above. Russell states (a, p. 47) that observations show that lacustrine sediments are usually not red.

——:—*Estuarine.* Regarding the color of estuarine conglomerates also no definite information is at hand. The Newark formation, which is believed by many to be of estuarine origin, is characterized by a deep red color in many of its members, but it may be questioned whether the formation is not fluviatile.

——:—*Glacial.* Among the more recent glacial deposits the latest, unweathered, are generally dark bluish or greenish gray in color, while the older, more deeply weathered accumulations, are often highly ferruginous. Of the ancient glacial deposits above described, the majority are said to be dark bluish, greenish, or grayish in color, while some of those in Australia are said to contain reddish brown clay slates, passing downward into grayish brown mudstones.

——:—*Crush.* No data bearing on the color of crush conglomerates are available for this discussion.

Bedding:—Marine. Marine accumulations in general possess a well-marked stratification, the beds grading upward from coarse to fine, where the deposits were laid by a transgressing sea, and passing horizontally seaward into younger and finer beds, as described by Hill. Variations in thickness and composition along the dip of the several beds are much greater than along the strike and all the beds are lens shaped in cross section, first thickening, then thinning seaward.

Cross-stratification and irregular bedding are common among the conglomerates and sandstones, and sometimes these coarser beds are interstratified with finer materials in lenses which thin out or are replaced in their own horizon by deposits of different texture. Local unconformities may occur, as where interbedded marsh deposits are

locally eroded. Ripple-marks may be indicated in some cases by cross-bedding, as in the Medina example described by Gilbert,[1] but mud-cracks, footprints and other impressions indicative of former extensive mud-flats would not be expected to occur in strictly marine deposits. Conglomerates formed by a transgressing sea may be expected to maintain a relatively moderate thickness over a wide area, as in the Cretaceous basal conglomerate of Texas. The Pottsville Conglomerate does not, however, conform to this expectation, for it maintains a great thickness in its southeastern portion but thins out rapidly northwestward, by the loss of its lower members. Such rapid diminution, though strongly contrasted with the Texas example, is entirely consistent with the idea of fluviatile origin.

——:—*Fluviatile.* The criteria given by Oldham in support of the fluviatile origin of the Gondwana sediments, summarize much of the data cited with regard to the bedding of fluviatile conglomerates. He says (a, p. 150–151): "The frequent alternation of coarse and fine beds, the frequency of current markings on the finer shales and of oblique lamination, due to deposition by a current, in the coarser sandstones and the circumstance of the upper portions of a bed, such as a coal seam, being locally worn and denuded where a coarse sandstone is deposited upon it, a phenomenon of frequent occurrence, are quite consistent with the theory of deposition in a river valley." Some other important features deserve notice. The gravel beds decrease rapidly in thickness laterally away from the streams by which they were deposited, as shown by the Siwalik and Bhábar accumulations in India, and by the great alluvial cones described by Drew, Dutton, and Johnson. Dutton states that in alluvial cones sections along the radii give the best stratification but that in transverse sections the stratification is less uniform and harmonious. Johnson speaks (*cf.*, p. 117) of the great debris slope, of which the present High Plains are but a remnant, as composed of "interlaced gravel courses penetrating a mass of fine material." Since deltas are essentially prolongations of river flood plains they will preserve in the main the characteristics of fluviatile deposits but in consequence of their being built forward into a body of water, instead of being spread out fan-like on the land, they present the additional feature of steeply inclined fore-set beds noted above.

——:—*Lacustrine.* The bedding of lacustrine sediments will tend on the whole to conform more closely with marine than with fluviatile

[1] According to Fairchild the "giant ripples" of the Medina sandstone represent former beach crests.

deposits, but in the normal cycle coarser sediments tend to encroach upon and overlie finer.

——:—*Estuarine.* Willis's statement (*cf.*, p. 121) is practically a summary of the available data on the bedding of estuarine conglomerates. The deposits are marked by frequent and irregular interbedding of coarse sands, sandy clays, and clays, cross-stratified beds, ripple-marked and sun-cracked mud surfaces, and channels scoured by transitory streams.

——:—*Glacial.* In glacial deposits sometimes a rude stratification is to be observed in till, and when the layers separate the surfaces usually show a polished or glazed appearance. Sometimes also included stratified beds, lenses or pockets of coarse and fine material occur. Ordinarily, however, the mass is completely unstratified and no assortment of its component materials can be observed. The fluvio-glacial deposits have already been noted as possessing all stages of stratification up to well-sorted sands and gravels with well marked cross-bedding. Where floating ice has dropped glacial debris away from shore the boulder-beds thus formed possess a well-marked stratification, as in the case of the deposits of India and New South Wales. The bedding may, however, be contorted and confused in places where the floating ice masses have stranded or scrubbed along the bottom.

——:—*Crush.* When true crush-conglomerates are formed the crushing movements have often been so intense as to destroy all traces of the original bedding.

Relations to Subjacent Rocks. Rocks of any of the types under discussion may rest conformably or unconformably upon underlying deposits, with the exception of crush-conglomerates. The latter, being the result of mechanical deformation, rather than of deposition, can scarcely be considered in this connection, though pseudo-unconformity may be produced as the result of the overthrust faulting or slickensiding of the deformed rock masses. No distinctive characteristics have been found to mark the unconformable contacts of the other types of rock with underlying masses, save in the case of the glacial conglomerates. In all cases cited where the deposits have been recognized as being truly glacial, they have been found in some exposures to rest upon definitely striated rock surfaces. Helland's contention for the glacial origin of the conglomerates in southwestern Norway is greatly weakened by his failure to discover such glacial markings beneath the rocks in question.

General Discussion.—The details of character and structure of

the several types of conglomerates have been set forth above. It is desirable now to make some comparisons to bring out more clearly the distinctions between the different types. For this purpose it will be convenient to continue the use of the scheme already employed.

Matrix. According to Geikie the smaller particles of detritus are generally less well rounded than those of greater dimensions (A. Geikie, p. 162). This is doubtless true of all water-laid deposits. Although the matrices of marine conglomerates are sometimes ferruginous they are probably characterized ordinarily by clean sands, cross stratified and fairly well assorted. Willis, speaking of beach deposits, says, (b, p. 487), "The sand is clean and characterized by marked and irregular cross-stratification." Russell (a, p. 45), referring to the incrustation of the grains in certain ferruginous deposits, observes that if the debris had been deposited in the ocean and exposed to the action of waves and currents, the sands would have been more thoroughly assorted than we now find them, and also that the attrition produced by the waves under such circumstances would have scoured off the incrustation of ferric oxide. Dutton, too, emphasizes the more thoroughly assorted condition of marine sediments as opposed especially to fluviatile deposits. As regards the latter Dutton states (p. 220) that material of all sorts is deposited everywhere, yet with a tendency to sorting. Probably the littoral deposits of lakes would approach marine deposits in uniformity of size and arrangement of particles, but with the absence of tides it is doubtful if these characteristics would be in general so highly developed.

Estuarine deposits are seen to consist in the main of mixtures of sand and clay not very well assorted but relatively fine. The matrices of crush-conglomerates would doubtless present much diversity in the size and shape but not in the material of their particles. Probably glacial deposits display the greatest variation in the character of the finer fragments which constitute their matrices. Fluviatile deposits may often approach them in heterogeneity of material and arrangement and in angularity of individual particles. One minute feature of distinction may, however, be noticed. In the case of small fluviatile fragments, which are only slightly rounded, the attrition will probably be equally developed on all corners or edges. In the case of similar glacial fragments, as shown by the microscopic study of the Dwyka Conglomerate (see, p. 130), one edge or corner of a particle may be smoothed or rounded while other corners or edges remain sharply angular. While, therefore, there is considerable variation in the matrices of the various types of conglomerate and one type shades into another, the marine deposits may be regarded as pre-

senting the most nearly perfect, and glacial deposits the least perfect, assortment and arrangement of particles, the intermediate stages being lacustrine, estuarine, fluviatile, and crush.

Pebbles. The preceding accounts have shown that the pebbles of marine and lacustrine conglomerates tend to be well sorted and well rounded, though they may be subangular in proximity to their sources. Shrubsole, noting the way in which pebbles slip over each other with the recession of each wave, remarks, "the pebbles become as a rule symmetrical and lose all traces of angularity" (Shrubsole, p. 315). Estuarine pebbles tend to be but imperfectly sorted and rounded and fluviatile pebbles may show all stages from confused heaps to well-stratified beds and from well-rounded forms to almost complete angularity. The difference between marine and fluviatile pebbles is thus expressed by Dutton: "Attrition" (in the fluviatile conglomerates of the High Plateaus) "is not ordinarily extreme. In most cases it is enough to indicate that the fragments are really abraded, though with no great loss of substance. The stones of sub-aqueous conglomerates, on the contrary, are almost always much worn and rounded. Again, the sizes of the stones" (in the fluviatile conglomerate) "range from a fraction of a cubic inch to several cubic feet; in rare instances to more than a cubic yard" (Dutton, p. 224). In crush-conglomerates the shapes and sizes are variable depending on the character of the rocks crushed and on the character and amount of the deforming force. No doubt the pebbles would often be distorted and contain fracture planes and tension cracks. Glacial pebbles are characterized by variety in composition, size, and shape. Their sizes and shapes may, however, be so successfully imitated by pebbles and boulders of fluviatile origin that it is only when the fragments are seen to bear the characteristic glacial striae or to be intimately associated with stones that are so marked that their glacial nature can be regarded as established. Even here caution is needed, for in land slides or mud flows striated pebbles may be produced, which closely resemble those developed by glacial action. In this connection it is worth while to note the view of Meunier, who suggested that even such extensive accumulations as the Dwyka Conglomerate might be the result of mud flows in which later movements had been induced by the action of percolating waters in removing finer material (Meunier, p. 121). It is probable then that the following order represents the relative regularity in size, shape, and arrangement of materials in the various types of conglomerate, though here too no sharply defined lines of separation can be drawn: marine, lacustrine, estuarine, fluviatile or crush, glacial.

Color. While it has been shown that marine conglomerates are sometimes ferruginous, the remarks of Russell and Willis already noted tend to show that such rocks are not, as a rule, highly colored. Lacustrine sediments have also been shown to be usually free from red color. The evidence brought out with reference to estuarine deposits is insufficient to make any general statement; they are, however, often considered to have a tendency toward a red color. Some of the fluviatile deposits described are shown to have highly colored red or purplish zones. Strahan, speaking of the characteristics of continental formations, says they have a common tendency to a red color (Strahan, p. 143–144). Crush-conglomerates, being induced as secondary structures in rocks already formed, partake of whatever color the parent rock may have possessed. Glacial conglomerates, as a rule, appear not to be highly colored, though the Australian boulder-beds are described as containing reddish brown members. Red color is therefore not a distinctive characteristic of any particular type of conglomerate formation, but it may be said to be more common in the fluviatile and perhaps in the estuarine types than among the other kinds of conglomerate.

Bedding. Marine formations have been shown to possess on the whole the best developed and most uniform bedding; while glacial formations exhibit the least developed and perhaps the most irregular stratification. Lacustrine and estuarine formations tend to resemble marine formations, while fluviatile deposits may be well stratified or on the other hand may so closely simulate heterogeneous glacial accumulations as to cause uncertainty as to their origin; witness the discussion of the Midland Pebble Beds of the Old Red Sandstone. Cross-stratification and lenticular masses of coarser and finer material are common in all these types but in the marine type the long axes of the lenses are more frequently parallel to the shore line, that is, to the original strike of the rocks, while in the case of fluviatile accumulations the long axes of the lenses are parallel to the courses of the stream threads by which they were deposited, that is, to the original dip of the rocks. All the water-laid deposits appear to increase in thickness and coarseness toward their source of supply. Other differences are cited by Strahan in his discussion of continental deposits. He states that the latter are not only unequal but alternate with erosion, so that fragments of one bed are included as pebbles in another; that they rarely contain marine organisms or such strata as usually compose marine formations, but that drifted plant remains are not uncommon, and that such liemstones as occur consist, when unaltered, of amor-

phous carbonate of lime and not of organic remains (Strahan, p. 143–144). Current markings, sun-cracks and footprints or other impressions common on exposed mud-flats, are frequent in estuarine and perhaps in fluviatile or lacustrine deposits but do not ordinarily occur in marine formations.

In crush-conglomerates no true bedding appears and all traces of the original bedding may have been destroyed. The bedding of ice-laid deposits is very obscure and that of fluvio-glacial deposits merges into that of true fluviatile deposits so that little or no distinction can be drawn. In summarizing the discussion of bedding it may be said that marine deposits give on the whole the most even and regular stratification, while fluviatile accumulations present the greatest variety. Ice-laid materials and crush-conglomerates show little or no bedding.

Relations to Subjacent Rocks. The main fact brought out by the investigation of the relations of conglomerates to subjacent rocks is that those formations of any age that have been proved to be glacial have been found to rest upon striated rock surfaces. The possession of heterogeneous structure, irregular and striated pebbles, while furnishing strong evidence of glacial action, cannot be considered as conclusive proof, for such structures and forms may be produced in other ways. When, however, such forms are found to rest upon a smoothly polished and striated rock surface, the weight of evidence is so great that no other explanation can be accepted.

Summary.— Marine sediments exhibit, on the whole, the greatest uniformity of composition and the most orderly arrangement of materials, while glacial deposits display the opposite characteristics. Lacustrine, estuarine, and fluviatile accumulations attain intermediate degrees of uniformity. Marine action tends to produce sheets of relatively uniform thickness over wide areas, while fluviatile action tends to produce interwoven linear bundles of coarser and finer materials, which may attain great thickness in the aggregate over limited areas, but which thin out more rapidly than is the case with marine deposits.

Each of the various types of conglomerate possesses features that are shared to some extent by other types. Thus there is no single feature which in itself distinguishes any particular kind of conglomerate. It is only when a number of features of one type are grouped and compared with a similar group of another type that definite distinctions can be made. Such a comparison is attempted in the accompanying tabular summary: —

Type	Marine	Lacustrine	Estuarine	Fluviatile	Crush	Glacial
Matrix	Clean sands, fairly well assorted, cross-stratified; angular to rounded grains.	Similar to marine; perhaps less well sorted, less clean, and less well-rounded grains.	Fine gravel and sand with much mud, unsorted, cross-stratified; angular to subangular grains.	Sands mingled with finer and coarser material, not well sorted, cross-stratified; angular to subangular grains.	Unsorted autoclastic fragments.	Heterogeneous mass of finer and coarser material, compact, angular grains of minerals and rocks; some fresh feldspar; some grains partially rounded and partially angular.
Pebbles	Generally local materials, fairly uniform size, well rounded; may be scratched by shore ice, landslides, etc., but not faceted nor snubbed.	Similar to marine, though perhaps less well sorted and rounded.	Local materials varying in size and not well sorted; subangular shapes on the whole; markings as in marine.	Generally local materials of all sizes up to masses of several tons, generally subangular but varying from rounded to angular; fragments of one stratum included as pebbles in another stratum of same formation. May be scratched by river-ice action, landslides, etc., but not faceted nor snubbed.	Varying size and shape, angular to rounded, showing portions of crests or limbs of folds; fracture planes; tension cracks. Autoclastic fragments.	Generally local materials, but a considerable proportion from distant sources. Little, if any, assortment, all sizes up to masses of several tons. Pebbles faceted, rounded edges, snubbed ends, polished and striated surfaces with striae generally parallel to long axis of stone but often showing two or more directions.
Color	May be ferruginous, but not usually highly colored.	Similar to marine.	Tendency to red color (?)	Many not colored but perhaps tendency to red color.	Depends on parent rock.	Generally dark grayish with bluish and greenish tints, occasionally ferruginous.
Bedding	Stratification generally well marked. Cross-stratification often well developed; in the normal cycle finer sediments encroach upon and overlie coarser materials; sometimes local unconformities, irregularities, lenses, etc., but *more regular* along the original *strike* than along the dip; limestones in the series composed chiefly of organic remains.	Conforms more closely with marine than with fluviatile deposits; in the normal cycle coarse materials encroach upon and overlie finer sediments. Limestones or marls of the series contain remains of fresh-water organisms.	Frequent and irregular interbedding of coarse sands and finer materials; frequent cross-stratification; ripple-marked and sun-cracked surfaces with organic and other imprint markings.	Frequent alternation coarse and fine beds; frequent current markings and oblique lamination; frequent local unconformities; irregularities in thickness and character, lenses, etc., but *less regular* along the original *strike* than along the dip; limestones infrequent but where they occur and are unaltered, they consist of amorphous carbonate of lime and not of organic remains.	No true bedding; all traces of original bedding may have been destroyed.	Till and corresponding ancient formations usually not bedded; sometimes obscure stratification and layers when separated show glazed and striated surfaces; sometimes pockets, lenses and beds of coarser and finer stratified material with cross-stratification included in the unstratified mass. Fluvio-glacial material shows all gradations from no stratification to well-marked fluviatile type. Marine glacial boulder beds show well-marked stratification and alternation of coarser and finer beds.
Relations to Subjacent Rocks	May be conformable or unconformable; nothing especially distinctive of marine action.	Same as marine.	Same as marine.	Same as marine.	Pseudo-unconformity by overthrust faulting or slickensiding.	Rests on striated, smoothed, and polished surfaces of older rocks or older portions of the same formation.

Lithology of the Roxbury and Neighboring Conglomerates.

Methods of Work.—More than two hundred specimens from the Roxbury and neighboring conglomerate regions have been examined in the laboratory. All of these have been studied by using the hand lens on natural fresh and weathered surfaces. Polished surfaces of fifty or more specimens, typical of their respective localities, have also been examined with low and higher power lenses.

The polished surface affords a very effective means for the study of many crystalline or clastic rocks. If the specimen is not too large it may be placed with its tray on the stage of a petrographic microscope. Then, with low power lens and reflected light, minerals and structures may be observed which are not well discerned in ordinary macroscopic study. If the specimen is not so shaped as to lie with its polished surface horizontal, it may be placed in a tray of sand, which, if carefully handled, will obviate the difficulty without endangering the microscope. A magnifying glass, mounted on a stand fitted with ball and socket joints, may be used with advantage to concentrate the light on the portion of the specimen to be inspected. This process has been employed by the writer in a number of cases. It possesses an advantage over the use of the thin section in that it permits the study of a larger surface of rock. The latter method, however, must still be applied in cases where minute details and careful determinations are required. More than fifty thin sections have been obtained and examined in connection with their respective specimens.

Scheme of Description.— In the accounts of conglomerates in the preceding chapter the writer has often found it difficult to secure the details needed for the present discussion. The rocks have been described by some of the writers in a somewhat haphazard fashion rather than in accordance with a definite plan. Some looseness, or at least indefiniteness, in the use of descriptive terms has often left doubtful the exact meaning of a given expression. For example, the term "well rounded" as applied to the shapes of pebbles is occasionally misleading. It was noted (page 117) in Johnson's description of the gravels of the High Plains that the pebbles are described as well rounded when in the photograph accompanying his account they appear subangular. Thus it is highly desirable, when the lithological character of rocks, or indeed when any object of scientific interest, is to be described, that some definite plan be formu-

lated to include each feature that may be expected to appear. The definite statement of the absence of any such feature is often as important as the mention of the presence of another, since it indicates that its importance was recognized but that search for it was fruitless. Such a plan serves to stimulate observation and to direct attention to characteristics perhaps otherwise overlooked.

In the following descriptions of the various rocks the writer has attempted to use the plan set forth (page 138). Since, however, the section entitled "Relations to Subjacent Rocks" applies to the larger relations of conformity and unconformity and cannot well be illustrated in hand specimens, that topic will be replaced by "Relations to Melaphyr."

Descriptive Terms. The descriptive terms now in use for the shapes of pebbles need more exact definition. In the present discussion the four following terms will be employed to express the comparative degree of rotundity attained by the pebbles of a conglomerate.

Angular. The fragments present sharp angles or edges with little or no evidence of attrition (Plate 1, A).

Subangular. The pebbles vary from almost angular fragments to smooth stones that have no sharp angles or edges but still retain relatively flat or irregular sides (Plate 1, B).

Rounded. The pebbles begin to lose their flattened and somewhat irregular shape and to approach the form of the ellipsoid or spheroid (Plate 1, C).

Well rounded. This term is reserved for pebbles that have acquired ellipsoidal or spheroidal forms. No specimen is at hand which illustrates this type well. Some of the pebbles in C and D (Plate 1) may be said to be well rounded.

It is obvious that no sharp line of division can be drawn in the use of such terms and that the personal equation must therefore enter to some extent into all descriptions where they are employed.

THE ROXBURY SERIES.—*Arkose.* Arkose occurs in several parts of the Boston Basin. In Medford the conglomerate is described by La Forge as passing into arkose and granite (La Forge, p. 75, 89). The arkose is somewhat kaolinized but consists of irregular grains of quartz and feldspar. Crosby speaks of arkose as occurring along the southern boundary of the Carboniferous series near the granite in Quincy, (n, p. 436). Outcrops occur on Gun Hill Road and on Randolph Avenue (ibid., p. 438). This rock has not been seen by the writer but it is described by Crosby as quite

granitic in aspect, though the feldspathic element is generally kaolinized and the rock shows slaty partings (ibid., p. 479). At East Dedham a very close relation exists between the granite and the overlying arkose and conglomerate. Outcrops on the east side of Mother Brook at Dedham IV, E 1 (Plate 7) and a quarter of a mile west at D 1 show rocks that appear as somewhat crushed or sheared granite but one part of the ledge at the latter locality appears gritty. At D 3, a few rods east of the railroad station, the rock is mostly arkosic but the matrix contains some small fragments of felsite and subangular, elongated, and subrectangular pebbles. In some places the rock at this locality is so granitic in appearance that it might easily be mistaken for granite. A polished specimen shows the feldspar to be relatively fresh. In the region of Wellesley and South Natick the conglomerate in the vicinity of the granite and felsite is highly feldspathic and felsitic.

Conglomerate: — Matrix. The matrix of the conglomerate throughout the Boston Basin consists largely of fragmentary quartz and felsite, the latter substance being present in almost every specimen examined. In addition there is a considerable percentage of feldspar and some quartzite, though these are by no means so universal constituents as the felsite. In some localities, especially at some of the Nantasket ledges, the matrix contains abundant epidote. In Brookline and Newton, especially on the southwest side of Walnut Hill (Boston VI, B 12, C 13, Plate 7), the matrix of the conglomerate has been impregnated with basic igneous rock, probably melaphyr, so that the latter envelops both the grains of the matrix and some of the pebbles.

The size of the grains is usually variable from very fine particles to fragments $\frac{1}{4}$ or even $\frac{1}{2}$ inch in diameter. The line of division between grains of the matrix and actual pebbles is often arbitrary and the rock in many cases grades from fine grains, less than $\frac{1}{32}$ inch in diameter, to large pebbles or boulders several inches, or even more than a foot, in diameter. In only five out of fifty specimens representing different parts of the basin were the grains of the matrix noted as fairly uniform in size.

The shape of the grains is almost universally subangular or angular. In only four of the specimens above mentioned were some of the grains rounded.

No definite arrangement of the grains in the matrix was observed except that induced by shearing. They were generally huddled together in greater or less confusion, except that in one case a rude stratification was noticed.

The cement of the conglomerate is usually silicious or felsitic, seldom argillaceous. In the cases where the cement is felsitic the rock is composed largely of that material; pebbles of quartzite, felsite, and granite, together with grains of quartz, occur embedded in a fairly homogeneous ground mass of felsitic material. The felsitic cement is particularly noticeable in localities near which felsite occurs *in situ*. In the vicinity of Mattapan and Hyde Park, for example, the felsitic element in the conglomerate becomes more and more abundant so that there seems to be a gradation between undoubted conglomerate on the one hand through felsitic conglomerate and felsite breccia to felsite on the other. Similar phenomena are noted at Medford, in parts of Newton, South Natick, and Nantasket. The whole succession is apparently similar to that described by Dutton in his account of the volcanic conglomerates of the High Plateaus, as noted on page 116. There the formerly clastic matrix of the conglomerate has been metamorphosed into homogeneous material entirely similar to the contained fragments (loc. cit.). A peculiar conglomerate that may be referable to the same type occurs north of President's Hill in Quincy (Boston IX, T 33). The matrix seems to be felsitic and the included fragments entirely granitic. In one specimen there were streaks that appeared to be microgranitic. In some places the rock resembles an indurated tuff. Specimens from this locality have been examined petrographically by T. G. White, who states that they look exceedingly like volcanic tuff with laths of plagioclase and stubby hornblendes. He says that unless the rock is in reality a true volcanic that has in some way enveloped the rounded pebbles we have a conglomerate surprisingly metamorphosed and recrystallized in the presence of neighboring igneous rocks (T. G. White, p. 124).

——:—*Pebbles.* An examination of the pebbles of the conglomerate shows that on the whole felsite in many varieties is the substance most abundantly represented, with quartzite and granite next in importance. Out of 65 specimens collected from all parts of the basin 50 were noted as containing felsite while 38 contained quartzite, and 25 granite. Other rocks much less frequently represented are slate, melaphyr, contemporaneous sandstone and grit, white quartz, and diorite.

The size of the pebbles is usually variable. In most localities the pebbles or fragments grade down to the grains of the matrix without any well-marked line of separation. In Medford the pebbles do not ordinarily exceed three inches in diameter. North of the narrow slate belt that passes through Chestnut Hill Reservoir the pebbles

decrease in size from an average of three or four inches at Newton Center to an average of about two or three inches at Auburndale. South of this same belt the size of the pebbles increases so that boulders eighteen inches in diameter are of frequent occurrence in Brookline, while farther south the size again decreases. Eastward, too, in the same zone the conglomerate is finer and somewhat more uniform. These latter features are well shown by the rock exposed at the great Tremont Street quarry on the north side of Parker Hill in Roxbury. In the conglomerate zone extending ENE from the Stony Brook Reservation the same general gradations in size north, south, and east are noted. Along the north shore at the northern extremity of Squantum and on the east shore of Huit's Cove at Hingham the conglomerate displays unusual variety in size, the pebbles ranging from less than an inch to more than four feet in diameter.

The shape of the pebbles is also variable. Of the 65 specimens above mentioned the pebbles in 32 were noted as unqualifiedly subangular, while in 20 they were described as subangular to rounded. Of the remainder 5 were not described, while 4 were angular and 4 rounded. On the whole it may be said that the tendency of the pebbles is toward rotundity rather than angularity but that in comparatively few instances can they be described as well rounded or even rounded. The term subangular appears to be applicable in the majority of cases. As a rule the finer conglomerates have the more rounded pebbles. The areas at Squantum and at Huit's Cove are no less remarkable in the shape than in the size of their pebbles. At the latter locality especially every variety of irregularity appears to be represented.

A careful search for markings that might in any way suggest glacial action met with no success. A few instances were observed of pressure striations, traceable to dynamic metamorphic action.

Evidences of deformation were numerous but usually only incipient stages were observed. The most frequent was shearing, which, though generally not intense, occasionally developed into schistosity. In some cases the pebbles were cracked, sliced, compressed, indented, stretched and bent but only to a comparatively slight extent. It has not been possible to correlate the localities of maximum deformation but the evidence now at hand seems to indicate the development of zones closely related to the axes of folding.

The pebbles of the conglomerate show little definite arrangement. Sometimes they are sparsely or thickly scattered through a mass of relatively fine material. At other times they form massive accumulations with comparatively little fine material. In a few cases a rude

stratification has been observed among the pebbles and a tendency to an arrangement with their long axes parallel. But usually no such features are to be observed. In general there seems to have been but little sorting, materials of many sizes and shapes often occurring at the same locality. Two extreme cases in this respect are the localities at Squantum and at Huit's Cove, already mentioned. There pebbles and boulders of all sizes and shapes are huddled together in great confusion. A field occurrence of the Squantum conglomerate is shown in Plate 3.

——: — *Color.* The color of the conglomerate presents varying tints in different combinations. Out of 50 representative specimens the following tints were present either singly or in combination, in the accompanying number of specimens: gray, 26; green, 20; purple, 19; drab, 9 ; red, 4; pink, 4; blue, 1. If red and pink are classed with purple it will be seen that gray and purplish tones are about equally distributed through the conglomerate and that green is next in importance. The purplish colors are not confined to any particular part of the basin but are rather widely distributed. They are not ordinarily intense; frequently they are only suggestions of the purplish or reddish tones. They are most strongly marked in some of the Nantasket ledges where they seem to be directly related to some of the effusive rocks of that region.

——:—*Bedding.* It has been shown above that the pebbles and matrix of the conglomerate show little definite arrangement. Occasionally streaks or zones of finer material may be recognized in the hand specimen. The larger features of bedding are reserved for the next chapter.

——:—*Relations to Melaphyr.* At several localities, notably on the southwest side of Walnut Hill and on the south side of Holyhood Cemetery on Hammond Street in Brookline, at Newton Upper Falls north of the Reservoir on the west bank of the Charles River and in the Arnold Arboretum the conglomerate is locally and irregularly impregnated with basic lava. Some of these localities are apparently remote from known outcrops of melaphyr, but others are near large masses of that rock, the only igneous rock of the region. It seems probable, therefore, that these impregnations represent melaphyr. In hand specimens the lava shows flow structure parallel to the contact with the conglomerate, and a finer grained darker zone immediately at the contact. Some of the pebbles of the conglomerate are enveloped and isolated by the lava. Under the microscope the igneous rock appears in tongues of partly devitrified basic glass containing magnetite in abundance and some well defined feldspar laths. There is some alteration

to epidote and chlorite. The igneous tongues partly enfold the pebbles and finally become dissipated among the interstices of the conglomerate. The data plainly show that the melaphyr, in these localities at least, is intrusive.

Sandstone and Slate:—Composition. The sandstones of the Roxbury series contain besides quartz a considerable proportion of felsite and feldspar. Of twenty-seven specimens examined seven contained felsite and four contained feldspar. The cement is usually silicious and the rock is firm and dense. The slates are sometimes sandy but they are generally argillaceous and compact.

——:—*Texture.* The sandstones are sometimes coarse grits with fragments ranging up to a quarter of an inch in diameter. Ordinarily, however, they are finer textured though their grains are often not well sorted. The fragments of which they are composed are seldom rounded but usually angular or subangular.

——:—*Color.* The colors of both the sandstones and slates are prevailingly gray, though other colors are represented singly or in combination. Of the twenty-seven specimens of sandstone examined seventeen (63 per cent) had gray tones, while in the case of the slate the percentage was not quite so high (thirteen out of twenty-two specimens or 59 per cent). In the case of the sandstones green and purple tints rank next in frequency of occurrence, the green appearing in 5 per cent of the specimens examined and the purple in 48 per cent. In the case of the slates, however, purple colors are more common than green, the percentages of occurrences in the twenty-two specimens examined being forty-five and twenty-seven respectively. Drab and red tints occur less frequently in both sandstones and slates but they are of relatively slight importance. If the reds are classed with the purples the enumeration of percentages for the slates will scarcely be affected but in the case of the sandstones the figures for purple and green colors will stand fifty-six to fifty-one in favor of the purple instead of forty-eight to fifty-one in favor of the green. Thus in the finer sediments the prevailing color is gray but purple and reddish tones are next in frequency and almost as abundant as the gray. Here again these colors are not confined to any particular locality but are on the whole widely distributed.

——:—*Bedding.* The evidence as to characteristics of bedding gathered from the hand specimens is unsatisfactory. Of fifty specimens examined only eight give any information bearing on this topic. A specimen of slate from Newtonville shows fine, even bedding and a dark gray slate from Quincy (Boston IX, V 32, Plate 7) is uniformly banded

with sandstone. A specimen of grit from Brighton (Boston V, C 31) contains irregular streaks of finer material in the coarse. Another specimen from the same locality shows layers of fine sand with beautiful purplish laminae of silt shading into them. The layers are much contorted and interrupted. Grit occurs between the dissevered ends and fills in the irregularities. A detached fragment of the fine sandstone also occurs in the grit. Still a third specimen from this locality shows lenticular development on a small scale, some of the lenses being not over an inch in length. Other specimens show some interbedding of coarser and finer sediments in the form of ill-defined zones. Cleavage is well developed in some of the specimens but usually forms an angle with the bedding in those cases where the latter can be determined. The evidence from the specimens above noted goes to show that in some places the conditions of deposition were fairly constant but that in other places there was less uniformity. The contortions noted in one of the specimens from Brighton were probably produced during the deposition of the sediments, for the rock does not appear to be metamorphosed. The disturbance of the layers is such as might well have been produced on unconsolidated, subaqueous sediments by the grinding action of stranded ice cakes.

——:—*Relations to Melaphyr.* The finer sediments show relations to the melaphyr similar to those above noted in the case of the conglomerate. Specimens from the ledges in the vicinity of the convent in Brighton (Boston V, H 27) show contacts of the melaphyr with sandstone that are very instructive. In one case the melaphyr contains a band of sandstone half an inch wide that has a dense ferruginous border one-eighth of an inch wide. Two small apparently detached, elongated areas of melaphyr within the sandstone near the border are also surrounded by the same kind of halo. In another case the melaphyr containing irregular amygdules of quartz and epidote cuts across the bedding of the sandstone. The layers are faulted and contorted near the contact. As the latter is approached the several layers bend and gradually become fused into a homogeneous, ferruginous mass in which the bedding can no longer be distinguished. Detached masses of sandstone are included in the melaphyr. The specimens show beyond question that the melaphyr in the ledges from which they were taken is intrusive into the sediments.

Summary of Roxbury Series. (1) Arkose occurs at several places in the Boston Basin. In some localities the feldspar is kaolinized but elsewhere, as at East Dedham, it is so fresh and the resemblance of the rock to granite is so marked that the arkose and granite are hardly distinguishable.

(2) The matrix of the conglomerate contains a large amount of felsite and considerable feldspar in addition to quartz. The grains are variable in size and shape and give little appearance of arrangement. The cement is generally silicious but near outcrops of felsite the mass of the conglomerate becomes more felsitic and tends to grade into that rock.

(3) Felsite, quartzite, and granite, in the order named, are the most abundant substances among the pebbles. The latter are variable in size and shape and are on the whole subangular. Gradations in size have been noted north and south of certain zones and generally eastward. Squantum and Huit's Cove furnish marked exceptions in this respect. No glacial markings were found but pressure striations and other evidences of deformation were seen.

(4) In general but little sorting has taken place among the pebbles. Materials of many sizes and shapes occur at the same locality.

(5) Gray and purplish colors predominate among the conglomerates but green is also frequent.

(6) The specimens and slides studied show melaphyr intrusive into the conglomerate.

(7) The finer sediments contain a considerable amount of felsite and feldspar but a much smaller proportion than the conglomerate.

(8) The sandstones and grits are often not well sorted and their grains are usually angular or subangular.

(9) Gray and purple tints predominate in the finer sediments, as in the case of the conglomerates.

(10) The bedding of the sandstones and slates shows at least some irregularities.

(11) In the cases studied melaphyr is intrusive into the finer sediments.

THE NORFOLK BASIN SERIES.— *Arkose.* In the Norfolk Basin the main outcrops of arkose occur at Pondville. The rock resembles granite but careful inspection reveals its true clastic character. In thin section it is seen to consist mainly of microperthite and quartz with the broken edges cemented with fresh quartz. There is some chlorite and ferruginous matter but the feldspars are fairly fresh.

Conglomerate: — Matrix. The chief materials that compose the matrix of the conglomerate in the order of their abundance are quartz, felsite and feldspar. Other substances of lesser importance are argillaceous material, secondary mica, chlorite, and epidote. The matrix of the Norfolk Basin Conglomerate differs from that of the Roxbury Conglomerate chiefly in the possession of a higher

percentage of feldspar and a greater development of schistosity and secondary minerals.

The size of the grains is variable up to about one-quarter of an inch in diameter and the shape also varies but is usually angular or subangular. Of fifteen specimens examined only two had grains at all rounded. No definite arrangement was noted; sometimes larger grains are scattered through finer material, or again, grains of varying size are huddled closely together.

The cement is usually silicious but sometimes it is felsitic, as in the case of the Roxbury Conglomerate. Where the matrix is schistose the cement is micaceous or chloritic.

——:—*Pebbles.* Felsite, quartzite, and granite, in the order named, are the most abundant constituents of the pebbles. Of twenty specimens examined fourteen contained felsite, thirteen quartzite, eight granite, and four quartz. Several other rocks of less frequent occurrence were noted, including slate, contemporaneous sandstone, pegmatite, and diorite. The felsite and quartzite are represented by many varieties. The granite is not like the bluish hornblende granite of Quincy, but, like that of the Boston Basin, is of the type found at Dedham and Randolph, with pink and green feldspars, biotite, and hornblende. The pegmatite and diorite were found in fine ledges by the roadside at Franklin VIII, R 21 (Plate 7). The former consists of albite and quartz and is the only specimen of its kind yet seen by the writer, in either the Norfolk Basin or the Boston Basin. Diorite is seldom found in the conglomerate.

The size of the pebbles varies greatly. The coarse conglomerate along the south side of the Blue Hill Range contains pebbles two feet or more in diameter. At the ledges referred to in the previous paragraph many of the pebbles are six inches in diameter and some of them attain the size of one foot or more. At other localities the pebbles do not reach such dimensions but on the whole the rock may be called fairly coarse, the pebbles varying up to three or four inches in length.

The shape is also variable. Of twenty-one specimens examined two contained angular pebbles, eighteen subangular, and five rounded. The same specimen may contain examples of each of these types. As in the case of the Boston Basin subangular types are the most abundant.

A search for striations or markings on the pebbles that might be ascribed to glacial action was unsuccessful in this area as well as in the Boston Basin. Pressure-striated pebbles were found to be more numerous, however, than in the latter area.

Many of the pebbles of the conglomerate bear evidence of deformation, chiefly in the form of shearing, but actual schistosity has been developed in some cases and in others the pebbles are sliced, crushed and stretched. On the whole these features may be said to be more highly developed in the Norfolk Basin rocks than in the Roxbury Conglomerate, though they are somewhat localized. The sections where they are best displayed are at Dedham II, C 4 and Franklin VIII, S 20, R 21 and M 21 (Plate 7). The sections along the south slope of the Blue Hills display some shearing but are relatively free from the other features.

——:—*Color.* The conglomerates of the Norfolk Basin present the same range of colors that are found in the Roxbury Conglomerate but in somewhat different order. The prevailing tones are green and gray while there is a considerable proportion of purplish tints. Of the twenty-one specimens examined seventeen had greenish colors, ten gray, six purple, including pink and red, and four drab.

——:—*Bedding.* In the hand specimens the arrangement of the materials of a rock so coarse as conglomerate is not well shown. In the case of four specimens, however, the pebbles were ill sorted and huddled together. The description of the larger features of arrangement and bedding will be given in a later chapter.

——:—*Relations to Melaphyr.* The melaphyrs, which play so important a part in the history of the Roxbury Conglomerate, have not been definitely recognized in the Norfolk Basin. A few of the pebbles found in the conglomerate resemble melaphyr but have not been satisfactorily determined. In two localities visited by the writer there is igneous impregnation, similar to that which occurs in the conglomerates of Brookline and Newton. Specimens from the south slope of Bear Hill (Dedham VII, E 18, Plate 7) show conglomerate impregnated by igneous rock. In thin section the igneous rock appears as irregular tongues of basic glass intruded into the conglomerate. At Franklin VIII, S 20 there is a suggestion of similar phenomena not so clearly shown. Thus it seems probable that melaphyr or some closely allied rock is represented in the Norfolk Basin.

Sandstone and Shale. The sandstones as indicated by the seven specimens examined consist chiefly of quartz with some felsitic and feldspathic material. Gritty and pebbly members are included in this group. The pebbles vary in size from a quarter of an inch in diameter to two inches and are usually subangular. The fragments in the gritty members vary from tiny grains to masses one-quarter of an inch in diameter. With the diminution in the number of coarser

grains the rock becomes a more normal sandstone. The fragments in both the grits and the finer sandstones are mainly angular and subangular and are not well sorted nor well arranged. The shales are sometimes arenaceous but generally they are argillaceous and well indurated.

The colors of the finer sediments include purple, red, green, and gray. On the whole the purplish or reddish colors predominate and are more intense and more characteristic of the rock than in the Boston Basin.

The bedding of the sediments of the Norfolk Basin is not usually well enough marked to be indicated in hand specimens, and will be detailed later when the field relations are treated.

Reference was made in a previous paragraph to the evidences of igneous intrusion among the conglomerates. At the east end of Ponkapoag Pond there are several bold outcrops of red sandstones, shale, and grit. In one of the latter there are somewhat uncertain evidences of similar igneous impregnation.

Summary of the Norfolk Basin Series. (1) The arkose at Pondville closely resembles granite. The contained feldspars are relatively fresh.

(2) The matrix of the conglomerate resembles that of the Roxbury Conglomerate but is more feldspathic and contains a larger proportion of secondary minerals. The grains are variable in size, shape, and arrangement.

(3) The pebbles are composed of practically the same substances in the same order as in the Roxbury Conglomerate. The specimens include one each of pegmatite and diorite. Along the south side of the Blue Hills the coarseness of the conglomerate exceeds that of the Boston Basin Conglomerate but elsewhere the two rocks are similar in that respect. The shape of the pebbles is usually subangular. Striations or markings are absent, except those due to deformation. Evidences of deformation are more marked in the Norfolk Basin than in the Boston Basin.

(4) The finer sediments are somewhat feldspathic and composed of angular or subangular fragments.

(5) The colors of the coarser sediments are prevailingly greenish gray and purplish, or reddish. In the finer sediments the red colors are more marked and form a more important feature of the rock than they do in the Boston Basin.

(6) The specimens examined show a less degree of assortment and arrangement than the specimens from the Boston Basin.

(7) At one locality definite impregnations of the conglomerate by basic igneous material, perhaps melaphyr, have been observed. At two other localities there are less certain indications of a similar character.

The Narragansett Basin Series.— *Arkose.* No specimens of arkose from the Narragansett Basin have been seen by the writer. The rock as described by Foerste is more decomposed than that of either the Boston or the Norfolk Basins. It now consists of detrital quartz from decayed granite with interbedded clay. The quartz grains are not well rounded. (Foerste, b, p. 269.)

Conglomerate: — Matrix. The materials of the matrix are apparently much the same in the Narragansett as in the Boston and the Norfolk Basins. The main constituents are quartz, feldspar, and felsite. Some specimens, however, contain more argillaceous and carbonaceous materials. Perhaps the most striking difference in the constituents of the matrices of the rocks in the three basins is the abundant occurrence of white mica in the Narragansett Basin and its absence in the others. The size, shape, and arrangement of the grains is similar to the corresponding features of the Norfolk Basin.

——: — *Pebbles.* Among the pebbles of the Narragansett Basin conglomerates the same general types of rock occur as in the other regions. Quartzite, felsite, and granite are the principal substances represented. There are, however, two important features of the pebbles that are not known to occur elsewhere in the regions under consideration: first, the appearance of Upper Cambrian fossils in pebbles of gray quartzite; second, numerous pebbles of muscovite granite. Although pebbles of gray quartzite of similar texture to those that contain the fossils are common in each of the basins, the fossiliferous pebbles are limited to the Narragansett Basin. A few such pebbles have been found within the basin but they are more numerous toward the southern margin, along the shore near Newport. In the drift at Martha's Vineyard they are very abundant, and scattered pebbles have been picked up along the beaches south of Nantasket (Woodworth, d, p. 109–113). The muscovite granite pebbles occur only in the Dighton Conglomerate, the upper member of the Narragansett series. They are abundant in the upper conglomerate at Attleboro. Pebbles of white quartz are abundant in some of the lower members of the Carboniferous series.

The size of the pebbles is variable. In the lower members the pebbles probably do not exceed three inches in diameter but in the

Dighton Conglomerate as exposed at Attleboro and in the Seekonk and Purgatory Conglomerates the pebbles are often eight or ten inches in their greatest dimensions. In the latter rock the pebbles exceed one foot in length and one specimen noticed by the writer measured nine feet in length. It is worthy of note that the coarsest conglomerate occurs at the southernmost limit of the exposed portion of the basin.

The pebbles are usually subangular or even rounded but in the basal conglomerate described by Foerste some of the pebbles are said to be angular (Foerste, b, p. 253). In some of the pebbles in the upper conglomerate at Attleboro re-entrant angles produced by intersecting joint planes have not been removed by abrasion.

No striations that could be attributed to glacial action were found on any of the pebbles examined but pressure striations and other evidences of dynamic metamorphic action were seen in a number of instances. The most remarkable cases of this kind were observed in the pebbles from Fogland Point on the east shore of Narragansett Bay. The rock is highly schistose. The pebbles have been flattened and stretched into spindle-shaped forms with rounded sides and ends, the elongation in many cases amounting to as much as 50 per cent or more of the original longer axis. The pebbles have been indented and sliced and sets of V-shaped tension cracks have been produced, some of which pass entirely through the pebbles. The pebbles thus deformed are chiefly gray quartzite but it is not known whether the latter corresponds to the fossiliferous quartzite at Newport. In some of the specimens examined by the writer the cracks developed in the pebbles looked as if they might have originated in the casts of fossil Oboli. Another striking instance of deformed pebbles is seen in the Purgatory Conglomerate. There the process has not been carried quite so far as at Fogland Point but the stretching and shearing have been intense. Plates 3 and 5 show field occurrences of the conglomerate at these localities.

——:—*Color.* The color of the conglomerate is usually gray with some greenish or purplish tints. Specimens from the northern part of the basin often show reddish tones of greater or less intensity.

——:—*Bedding.* No well-defined arrangement of pebbles or bedding of the conglomerate was shown in the hand specimens. Field observations will be given later.

——:—*Relations to Igneous Rocks.* No specimens illustrating the relations of the sedimentary series to the igneous rocks of the basin are at hand. Woodworth has described the occurrence of diabase and

felsite near North Attleboro. The account of these features is included under the heading "Relations to Igneous Rocks" on page 233.

Sandstone and Shale. The coarse sandstones or grits contain in addition to quartz a considerable amount of feldspathic and felsitic material. In the finer sandstones the rock is more quartzose. White mica is an abundant constituent. The shales are sometimes arenaceous or carbonaceous and are often fossiliferous. Usually, however, they are argillaceous and fairly compact.

The grains of the sandstones are variable in size ranging from tiny particles to fragments three-eighths of an inch in diameter. In the specimens examined the grains were chiefly angular and subangular. None were rounded. There was little arrangement of the particles. The cement was usually silicious.

The colors of the finer sediments are generally grays, sometimes with tints of green but often shading to dark or gray black. Reddish and purplish colors are also important and especially characteristic of specimens from the northern parts of the basin.

The bedding is not well displayed in the hand specimens. The features observed in the field are set forth in the next chapter.

Summary of the Narragansett Basin Series. (1) The arkose of the Narragansett Basin is much more decomposed than that of the Boston or Norfolk Basins.

(2) The matrix of the conglomerate agrees in texture and general composition with that of the Norfolk and Boston Basins, but it contains more carbonaceous material and is characterized by the abundant occurrence of white mica.

(3) The pebbles of the conglomerate consist largely of quartzite, felsite, and granite. The striking features are: — the occurrence of fossiliferous quartzite pebbles and pebbles of muscovite granite; the more frequent occurrence of the fossiliferous pebbles and the greater coarseness of the conglomerate toward the south; the remarkable deformation of the pebbles at the Fogland Point and Purgatory localities.

(4) The finer sediments are often fossiliferous and carbonaceous and are characterized by an abundance of white mica.

(5) The colors of the conglomerates are usually grays with greenish and sometimes reddish tints. The sandstones and shales are generally grayish to black. Specimens from the northern part of the basin, whether of conglomerates or finer sediments are usually of a red color.

THE HARVARD CONGLOMERATE:— *Matrix.* The matrix of the

Harvard Conglomerate consists of grains of quartz and small fragments of dark schist and quartzite inclosed in fine schistose material. The component materials vary in size from minute particles to masses a quarter of an inch in longest dimension. None of the grains appear rounded but all are either angular or subangular. The larger masses are scattered among the finer and all are bound in a silicious or micaceous cement. In thin section the matrix is highly schistose, consisting of quartz and mica with large crushed quartz grains that trail away into the finer material.

——:—*Pebbles.* The pebbles consist of gray quartzite and dark gray schist. The dividing line between the smaller pebbles and the larger grains of the matrix is arbitrary, for one grades into the other. The pebbles ordinarily do not exceed three inches in length. They are subangular, elongated, and irregular and some are almost round. No markings indicative of glacial action were observed upon them. Evidences of deformation are numerous. The pebbles show stretching, with augen-structure. Some of them appear to be disconnected pieces of the same stratum, with rounded ends, and with augen-shaped pieces and fine schistose material between the separated parts. Sometimes the pebbles look as if a sheared and stretched layer had been broken up into more or less rounded or oblong masses which now lie close together, and are more or less enveloped by finer, schistose fragments of the same layer. Two directions of shearing appear in the specimens, one parallel to the stretching and the other making an angle of about 45° with the first. There appears to be no well-defined assortment of the pebbles. In thin section a pebble of the quartzite is very fine and even in texture. Each grain shows some attrition and is subangular or even rounded. The pebble as a whole shows little sign of strain, though there appear to be some shear planes.

——:—*Color.* The main color of the Harvard Conglomerate is gray with greenish and whitish tints, the latter especially on weathered surfaces. In such places the matrix and the rock immediately below the surface are quite ferruginous.

——:—*Bedding.* The features of bedding are not displayed in the hand specimens.

——:—*Sandstone and Grit:* A schistose greenish gray sandstone shading into grit accompanies the conglomerate. The sandstone is fine grained and the grit shades into the conglomerate.

——:—*Relations to Igneous Rocks.* No igneous rocks appear in contact with either the conglomerate or sandstone and no rocks of such nature are included as pebbles in the conglomerate.

SOURCES OF MATERIALS OF THE CONGLOMERATES. — *Felsite.* Many varieties of felsite are represented in the conglomerates, especially of the Boston and Norfolk Basins. The classification of these varieties and the study of their distribution in the conglomerate, together with the determination, if possible, of the localities from which they were derived, form an interesting problem, but it involves detailed studies beyond the scope of this paper. In general it may be said that most of the felsitic pebbles resemble rock now exposed in the environs of the Boston Basin. This point, together with the fact that the conglomerate frequently becomes more felsitic in the vicinity of felsite areas and appears to grade into felsite breccias and then into felsite, indicate that much of the material of the conglomerate was locally derived and not transported any great distance. There are some doubtful varieties of felsite that may or may not be represented by rocks now exposed in the vicinity of the Boston Basin. Such are certain pebbles collected by H. J. Wiswell from the Roxbury Conglomerate in the vicinity of the Bird Street station of the New York, New Haven, and Hartford Railroad. These pebbles present striking resemblances to certain facies of the Blue Hills porphyry but when compared in the laboratory with a number of specimens representing different facies of that rock they were not definitely identified. Fragments of the Blue Hills porphyry are not certainly known to occur in the Boston Basin but Crosby has vigorously asserted that this rock is abundantly represented in the pebbles of the Norfolk Basin Conglomerates (n, p. 471).

Quartzite. Several varieties of quartzite are represented in the conglomerates of all three of the basins under consideration and quartzite forms the principal rock in the pebbles of the Harvard Conglomerate. From the abundance of quartzite pebbles in all the conglomerates it is certain that large areas of that rock must have been exposed at the time the pebbles were formed. Quartzite occurs in disconnected belts among the crystalline highlands to the north and west of the Boston Basin. This points to the northern and western highlands as possible sources of that rock and to a southward and eastward transportation of the material. In the Narragansett Basin, on the other hand, the coarse upper conglomerates become coarser and more highly quartzitic toward the south, the very largest pebbles being observed in the Purgatory Conglomerate near Newport. These facts point to a southerly source for at least the upper conglomerate. The evidence from the fossiliferous quartzite pebbles favors the same view. These pebbles become more frequent in the conglomerate

toward the south. According to Walcott the nearest place where quartzite containing the same fauna is exposed is at Great Belle Island near Newfoundland (Walcott, b, p. 327). If this place is accepted as the probable source of these pebbles it is necessary to invoke the aid of some agent of transportation powerful enough to carry pebbles of large size for great distances without permitting them to be comminuted during the process. Such a view would favor the idea of glacial action as advocated by Shaler (Shaler et al., p. 57–59). It is possible, however, to conceive the existence of a land mass, to the south and east of the present coast, large enough to supply the materials observed in the conglomerate. The marked increase in the coarseness of the conglomerate and in the number of fossiliferous pebbles in that direction tends to favor such a view.

The distortion of the pebbles of the Purgatory Conglomerate has been such as almost completely to obliterate any traces of fossils, so that it is not definitely known whether the great pebbles in that rock really belong to the fossiliferous quartzite. The writer saw some indications in the rock at the shoreward end of the Purgatory Peninsula that strongly suggested the occurrence of Oboli in the large quartzite pebbles of that locality. At the southeast and southwest of the Narragansett Basin quartzites occur *in situ*. Those to the southwest at least have furnished material to the conglomerates but they do not contain fossil Oboli (Foerste, b, p. 382).

The quartzite of the Harvard Conglomerate is unlike that of neighboring localities in having small grains of uniform size, showing a considerable degree of attrition. Professor Emerson, in conversation with the writer, suggested that the quartzite represented an aeolian deposit. Daubrée has shown that in water-laid sands the grains less than one-tenth of a millimeter in diameter are angular (Daubrée, p. 256). In wind-blown deposits coarse and fine grains alike are more or less rounded.

Granite. The granites most frequently represented in the conglomerates of the Boston and Norfolk Basins are a fine grained pinkish variety, containing little ferro-magnesian material, and a coarser type corresponding to the granites now exposed at Dedham, Randolph, and Cohasset, and consisting of quartz, pink and green feldspars, and biotite with hornblende. Similar, though not certainly identical, granite occurs in the northern highlands in considerable abundance and is typically exposed near Saugus. No granite of the Quincy-Lynn variety (bluish gray hornblende granite) has been seen by the writer in any part of the conglomerate. The occurrence of granite both

north and south of the basins in question similar to pebbles included in the conglomerate, together with the intimate relations of conglomerate, arkose, and granite at certain localities, as at East Dedham, again point to the local origin of the materials in the conglomerate and militate against the idea of transportation from a distance.

In the Narragansett Basin the same granite appears in the pebbles of some of the lower members but in the Dighton Conglomerate at the top of the series no such pebbles occur. There is, however, at this horizon a considerable abundance of muscovite granite, not represented elsewhere in the series. Muscovite is also plentiful in the upper sandstones and grits. The nearest localities known to the writer where rocks that could have furnished such materials are exposed are in the crystalline highlands northwest of the Boston Basin. If the rocks there exposed are considered as the source of the pebbles in the Dighton Conglomerate and of the muscovite in the sandstones it is necessary to assume the direction of transportation of the materials in the Narragansett Basin to have been from north to south rather than from south to north as indicated by the quartzite. On the supposition that the muscovitic material came from the north, its absence in the Boston and Norfolk Basins may be explained by the assumption that higher beds containing this material have been eroded away. If, on the other hand, it is supposed that the muscovite granite, like the Obolus quartzite, may have been derived from some land mass at the south, now no longer extant, it is difficult to account for the absence of the muscovite granite in the conglomerate at Purgatory. The latter is believed to be the stratigraphical equivalent of the Dighton Conglomerate, though it has not been proved that such is the case (Woodworth, d, p. 134); if therefore both quartzite and muscovite granite came from the south it would seem that both should be represented in the conglomerate. Perhaps the Purgatory Conglomerate represents a lower horizon than the Dighton Conglomerate. If such were the case the muscovite granite may not have been exposed to erosion when the quartzite conglomerates were forming. In view of the stratigraphical and structural relations made out by Woodworth and Foerste this supposition does not seem probable. It appears more likely that material was supplied to the conglomerate from both the north and the south. This supposition is favored by the decrease in the amount of muscovite granite southward and the increase of fossiliferous quartzite in the same direction. The occurrence of the pegmatite pebble in the conglomerate of the Norfolk Basin (page 161) indicates that the muscovite rock series may not be entirely absent from the Norfolk

Basin rocks, for pegmatite is a frequent associate of the muscovite granite in the highlands northwest of the Boston Basin.

Slate. Slate pebbles occur more commonly in the conglomerates of the Boston and Norfolk Basins than in the Narragansett Basin. The Lower and Middle Cambrian slates at Braintree and Weymouth indicate a local source for these materials.

Sandstone, Grit, and Melaphyr. Occasional pebbles of greenish gray sandstone and grit, entirely similar to members of the conglomerate series, indicate that contemporaneous erosion accompanied the deposition of these rocks. Similar evidence is afforded by the occurrence of melaphyr pebbles in certain parts of the Roxbury Conglomerate.

Summary of Sources. (1) The abundance of felsite, granite, and quartzite pebbles in the conglomerate, together with the occurrence of exposures of these rocks in proximity to the several basins, indicate that the material is locally derived and has not been transported great distances.

(2) The generally local nature of the deposits militates against the idea that the fossiliferous quartzite pebbles came from Great Belle Island, while the increasing frequency of these pebbles toward the south and east indicates a probable source in a land mass, now no longer extant, in that direction.

(3) The muscovitic material of the upper members of the Narragansett series was probably derived from areas of rocks of that type now exposed in the highlands northwest of the Boston Basin.

(4) The materials of the conglomerates were therefore probably supplied from sources both north and south of the present areas and not from any single direction.

(5) The deposition of the sediments was accompanied by contemporaneous erosion.

(6) The quartzite of the Harvard Conglomerate is unlike that of neighboring regions and resembles an aeolian deposit.

General Summary.— (1) The sediments of the three basins show great similarity in character, composition, and color, but red colors are less intense in the Boston Basin than in the others.

(2) In all three basins the sediments are not very well assorted. Materials of many sizes and shapes are found in the same deposit.

(3) The pebbles cannot generally be described as well rounded, but rather as subangular to rounded. The grains composing the grits and sandstones and the matrices of the conglomerates are usually more angular.

(4) The coarser sediments of all the basins are somewhat feldspathic but in those of the Norfolk Basin this feature is most highly developed.

(5) All the basins give some evidence of contemporaneous igneous action. These features are most strongly marked in the Boston Basin and least developed in the Norfolk Basin.

(6) The conglomerates of all the basins bear evidence of contemporaneous erosion.

(7) Evidences of dynamic metamorphism occur in all the basins but the metamorphism has not been intense except locally. Its effects are most marked in portions of the Narragansett Basin.

(8) The Narragansett Basin is further characterized by the occurrence of coal beds, fossiliferous shales, and carbonaceous material in the finer sediments and by muscovite, muscovite granite pebbles, and pebbles of fossiliferous quartzite in the coarser sediments.

(9) The distribution of the muscovitic material and of the fossiliferous quartzite suggests transportation from both northerly and southerly sources, but not for any great distances.

(10) The local nature of the other sedimentary materials is opposed to the idea of the importation of material from Great Belle Island or other northeasterly sources by glaciers.

(11) The Harvard Conglomerate is unlike the other conglomerates in character, composition, and appearance. The quartzite pebbles contained in it may be of aeolian origin. It has suffered intense dynamic metamorphism.

Stratigraphy of the Roxbury and Neighboring Conglomerates.

General Statement.—Some field data bearing on the lithology of the sediments have already been given in connection with the discussion of the hand specimens. In this chapter the intention is to set forth only those facts that have to do with the distribution, textural variation, and bedding of the rocks and with the relations of the series to the subjacent terrane. Structural data will be presented in the following chapter in connection with the discussion of the work of others.

The Roxbury Series.—*Distribution:*—*Arkose.* In the Boston Basin deposits of arkose occur at Medford, East Dedham, and along

the northern border of the granite west of Quincy. In Wellesley and South Natick also the conglomerates and grits in the vicinity of granitic or felsitic areas are highly arkosic or felsitic.

——: —*Conglomerate.* By reference to the map (Plate 7) it will be seen that the conglomerate of the Boston Basin is separated into three elongated areas by nearly east-west bands of slate. The conglomerate masses thus separated are relatively broad at their western ends and diminish in width eastward until they disappear beneath the slate or terminate at the sea. In addition to these larger areas two important isolated smaller areas of conglomerate occur in the southeastern part of the basin at Hingham and Nantasket and an irregular tongue of uncertain dimensions projects southwest from the vicinity of Newton Lower Falls through Wellesley and South Natick. The major conglomerate bands are more or less interrupted toward the west by masses of melaphyr and the two southern bands are split at their western ends by masses of the underlying felsite or granite that project eastward from Needham and Hyde Park.

——: —*Sandstone and Grit.* Sandstone and grit are not of sufficient abundance to form units that can be mapped but they are important and sometimes conspicuous members of the conglomerate series. They are interbedded with the conglomerate and shade into it. While they sometimes occur as indefinite zones or streaks within the conglomerate toward the central parts of the great conglomerate bands, they appear more frequently along the northern zone of the northern band and along the north and south borders of the other bands. They are also more abundant toward the east than toward the west.

——: —*Slate.* Slate bands extend westward between the conglomerate areas toward the western border of the basin. Eastward they broaden and appear to merge into the great mass of slate that is believed to underlie Boston Harbor. On the north and on the south of the general conglomerate mass extensive areas of slate occur which appear to merge around the eastern ends of the conglomerate bands with the narrow slate zones. A narrow slate band accompanies the southwest extension of the conglomerate through Wellesley and South Natick. At its northeastern end direct connection with the broad slate area of Somerville and Cambridge is not observed but the evidence of the few available outcrops seems to show that such connection exists. Along the borders of the conglomerate areas the slate is interbedded with conglomerate and sandstone, into which it appears to pass conformably. So far as field evidence goes the slates thus interbedded and interbanded with the conglomerate appear to be identical with the

larger slate areas to the north and south. This relation, however, has been questioned and will be discussed in the following chapter.

——: — *Associated Melaphyr.* Accompanying the conglomerate series are important masses of melaphyr that occur in isolated areas. The main exposures are indicated on the map. At Brighton the melaphyr is seen in contact with sandstone and slate. South of Bald Pate Hill in Newton, at Hingham, and at Nantasket it is seen in contact with conglomerate. Thus the occurrence of the melaphyr does not appear to be confined to one horizon. In addition to the actual exposures of the melaphyr there are a number of places where the conglomerate has been impregnated with the melaphyr in the manner described in the preceding chapter. This fact, together with the fact that at certain places, as at Nantasket and at Hingham, the conglomerate is interbedded with the melaphyr, so that fragments of the latter occur in the former, indicate that the melaphyr is contemporaneous with the sediments and was intruded or outpoured before the latter were consolidated.

Texture of the Conglomerate. In general it may be said that there is a gradation in the coarseness of the conglomerate toward both the north and the south from the slate belts. Just north of the Chestnut Hill slate belt the pebbles of the conglomerate average three or four inches in diameter while farther north along the main line of the Boston and Albany Railroad outcrops show a somewhat smaller average, two or three inches. The conglomerate along a north-south line from Newton Center to the railroad shows many alternations of sandstone and grit. South from the same slate belt the alternations of sandstone and conglomerate give way to very coarse conglomerate, with little indication of bedding. At ledges three-quarters of a mile west of Walnut Hill (Boston III, Y Z 12) the boulders of the conglomerate attain the size of two and one-half feet. At other localities in the region of Brookline and Newton similar coarse conglomerates are found. South toward Roslindale, the conglomerate again shows alternations of grit and sandstone which appear to pass conformably into the slates. Eastward the conglomerate has smaller pebbles and becomes more gritty. At the Tremont Street quarries (Boston V, S T 35), for example, the pebbles average one-half to two inches and at the quarries a mile and a half south (Boston VI, U 4) they average three inches in diameter. Similar features are noted, though not so well defined, in the southern conglomerate area.

The distribution of the conglomerate and slate areas and the frequent alternations of coarser and finer material near the slates indicate

that the coarse conglomerate occupies a stratigraphically lower position in the series than the alternating beds. This fact will be more clearly brought out when the structure is discussed.

It must not, however, be assumed that the heavy conglomerate is uniformly coarse throughout the Newton-Brookline area. The occurrence of boulders as large as two feet in diameter is rather local. There are, indeed, many ledges in the region where boulders of this size occur, but often in close proximity to them conglomerates of much finer texture appear. Thus in the ledges west of Walnut Hill (Boston VI, A 12, B 12, C 12–13) the pebbles average only one and a half to three inches, while the coarse conglomerate above mentioned is only a few hundred yards away.

Among the finer conglomerates a similar lack of uniformity is to be noted. In places where the pebbles average two or three inches in diameter pebbles six to ten inches in diameter not uncommonly appear scattered among the smaller ones. Even where the rock is largely grit, scattered pebbles more than one foot in diameter may be seen. This is well exemplified at the large quarry south of the Arnold Arboretum (Boston VI, M 16). Layers of coarse conglomerate are not infrequently interbedded with sandstone or grit apparently well up in the series, as in the remarkable outcrop on the north side of North Beacon Street in Brighton (Boston V, H 26), where pebbles of granite and other rocks more than one foot in diameter occur. This ledge has given rise to some controversy because of the appearance of slate masses that resemble clastic material but are two feet or more in length and nearly a foot in width. It has been maintained on the one hand that the slate masses are pebbles and on the other that they are pockets of slaty material laid down during the deposition of the conglomerate. After a careful study of the ledge the writer is inclined to concur in the latter opinion, as regards the larger masses at least. It is difficult to see how slate shingle of that degree of coarseness could escape comminution by the large pebbles of granite and quartzite so abundant in the same deposit. The occurrence of contemporaneous grit among the pebbles indicates contemporaneous erosion during the deposition. Some of the features above described are shown in Plate 2. The conglomerate at Squantum described in the previous chapter affords another remarkable instance of irregularity of deposit (Plate 3).

While therefore it is true that there seems to be a gradation in coarseness of material from the conglomerates of Brookline to the sandy and slaty sediments north, south, and east, it depends not so much upon the size of the individual masses, for coarse and fine

materials seem to be deposited together, but mainly upon the relative proportions of these two.

From the studies of the previous chapter the shape of the pebbles of the conglomerate has been shown to be subangular to rounded, while the finer fragments are generally subangular to angular. These features are very clearly shown in the field. The smaller pebbles, which usually attain the more rounded forms, are still in many cases subangular, while the large masses one foot or more in diameter are subangular or even angular.

Bedding.— The bedding of the conglomerate is best displayed along the borders of the several areas where frequent alternations with the finer sediments occur. In the central zones of the conglomerate areas, where finer material is scattered among the pebbles with little or no definite arrangement, it is difficult or impossible to determine the bedding. The attitude of the pebbles in the rock helps but little for they are often so huddled together that the flat sides do not seem to lie in any particular plane. In the Newton-Brookline area, for example, the bending is not easily determined while farther north or south near the borders of the slate belts the attitude of the rocks is fairly clear. The pell-mell arrangement of the pebbles in the coarser conglomerates and the scattering of large pebbles and boulders through finer sediments indicate rapid and irregular deposition. Two general forms of bedding are here distinguished: *bands*, where the upper and lower boundaries of the several strata are parallel or roughly so, and *lenses*, where the upper and lower surfaces of a layer converge. Sometimes only a portion of a lens may be seen, in the form of a wedge. In such cases the corresponding portion may be concealed by displacement or by some covering or perhaps it may have been eroded away.

——:—*Bands.* In the Boston Basin banding is the prevalent type of bedding and is the feature commonly relied upon for the determination of the attitude of the strata. It is by no means a constant characteristic, however. Of the 283 outcrops of conglomerate, sandstone, and slate, visited by the writer and described in his field notes, only 101 showed banding. Most of the observations recorded occur on the Boston sheet. In the western strip (Boston II and III) eighteen out of seventy-one outcrops (about 25 per cent) show banding. In the central strip (Boston V and VI) fifty of the 131 outcrops noted (about 38 per cent) are banded, while in the eastern strip (Boston IX, including the adjacent areas of Boston Bay III and VI) thirty-eight out of seventy outcrops (about 54 per cent) display similar features. The figures given are not absolute but they serve to show a

steady increase eastward in frequency of occurrence of well-defined bedding, corresponding to the increase in the proportion of finer materials in the conglomerate. A similar, though not so pronounced, increase takes place along a north-south line with reference to the slate belts. In Boston II four of the eight occurrences of banding are within a mile of the northern slate area. In Boston III, seven of the ten banded outcrops observed lie within a mile or a mile and a half of the Chestnut Hill-Newton Upper Falls slate belt. In Boston V the case is not so clear. Only eight of the thirty-one outcrops described are banded but these appear to have a fairly uniform distribution with reference to a north-south line. Boston VI is crossed by the Chestnut Hill slate belt on the north, the Roslindale slate belt in the center and the Neponset slate in the southeast. The forty-two banded outcrops recorded appear on the whole to be symmetrically arranged with reference to the slate belts, so that the coarser conglomerates with less clearly defined bedding occupy axial positions with reference to the conglomerate zones. In Boston IX and in Boston Bay III and VI the outcrops of banded conglomerate are also in proximity to the slate areas.

The bands by which the conglomerate is marked may be of coarser conglomerate in fine or *vice versa*, or of grit, sandstone, or shale. Their outlines are generally sharply and definitely marked. Sometimes, however, they are but poorly indicated and the bands become ill-defined zones of texture finer or coarser than the enclosing rock. If such a band is narrow it appears as a mere streak. The occurrence of these indefinite zones or streaks is relatively infrequent. Of the 283 outcrops of the Roxbury series recorded by the writer only fourteen (about 5 per cent) were characterized by such zones.

——:—*Lenses.* The occurrence of lenses in the Roxbury Conglomerate is much less frequent than might be supposed. The writer's field notes show only twelve localities. Probably the figures in this case and in that of the streaks above mentioned are too low, but the fact remains that both of these types of bedding are relatively uncommon. The lenses are found at several localities in Boston II, III, VI, and IX and Boston Bay VI. The largest one observed occupies the lower part of a ledge exposed for fifty feet on the grounds of the Hospital for Women and Children in Jamaica Plain (Boston VI, UV 7). The lens consists of angular fragments from half an inch to one and one-half inches in length and has a gentle southeasterly dip. At the west it terminates a few feet from the end of the outcrop and eastward it passes beneath the soil cover so that its true dimensions can-

not be determined. In the widest portion exposed it does not exceed three feet in width.

Another good example (Figure 4 A) is found in the coarse conglomerate on the north side of Boylston Street just west of Thompsonville (Boston III, S 6–7). The lens is composed of sandstone indistinctly cross-bedded and is eighteen inches thick. At the eastern end it is sharply defined and its upper surface shows ripple-marks. The strike

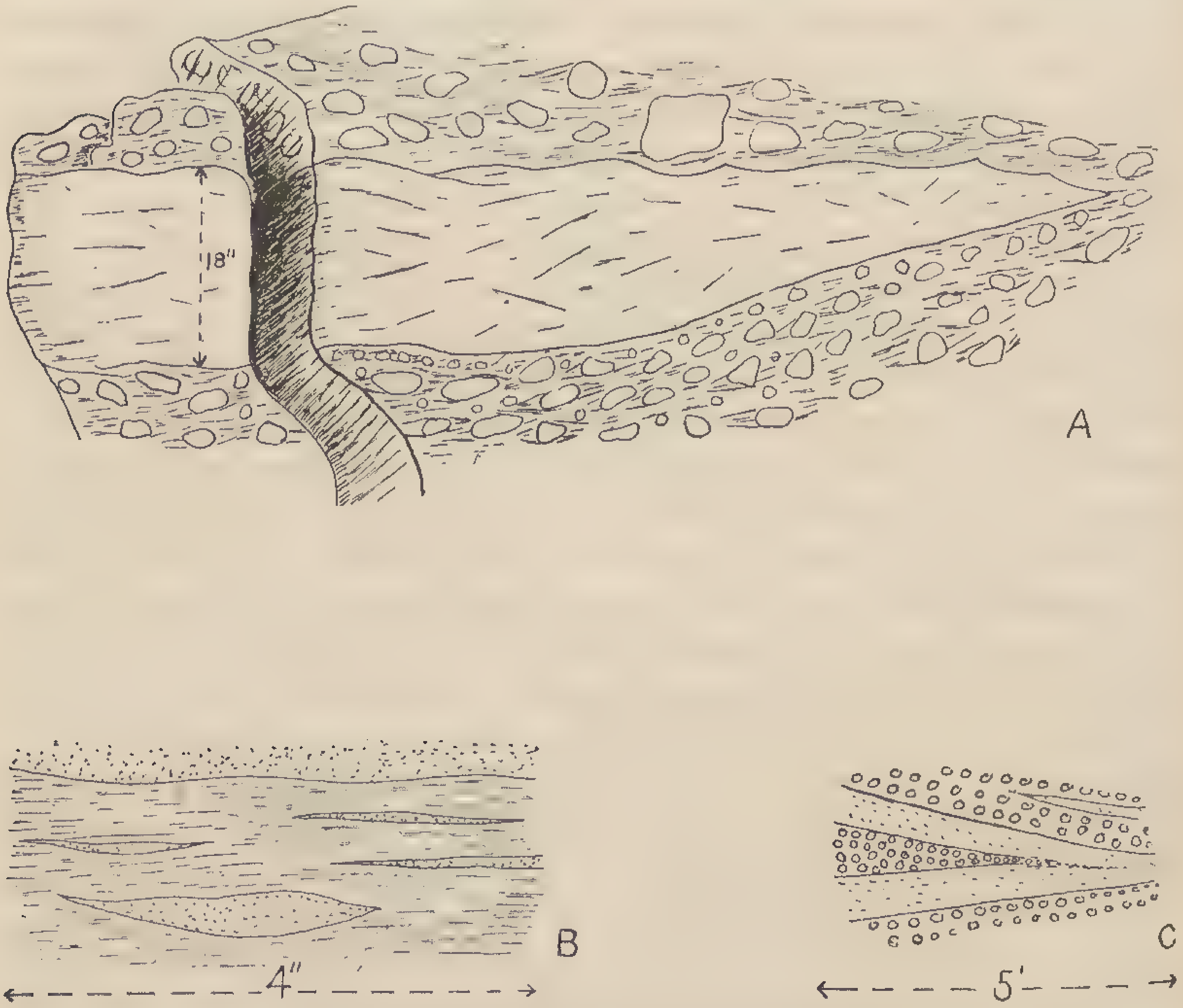

FIG. 4.— A. Indistinctly cross-bedded lens of sandstone in conglomerate west of Thompsonville.
B. Lenticular structure at Auburndale.
C. Lenticular structure at Roxbury.

is nearly east-west and the dip about 30° north. A few rods east another similar lens appears.

In some localities lenticular structure occurs on a minute scale. Such an example is found in the ledges on the north side of Commonwealth Avenue in Auburndale (Boston II, C 31). Conglomerate, sandstone, and slate appear interbedded. The sandstone forms small lenticular masses in the slate as indicated in Figure 4, B.

Lenses of conglomerate and grit occur at other localities. The observed examples as seen in cross-section do not appear to form linear bundles nor imbricated masses, unless the arrangement indicated in Figure 4, C can be so considered. On the contrary, the lenses appear as separate, independent bodies with roughly parallel axes and lie in the same horizon or in parallel horizons. The available evidence, however, is so scanty that little reliance can be placed upon it.

——:—*Cross-bedding.* According to the observations of the writer cross-bedding is not an important characteristic of the sediments of the Boston Basin. Of the 283 outcrops recorded only seven show cross-bedding and even in some of these cases it is ill defined. Usually this feature is associated with sandstone layers or lenses but in one or two instances it occurs in layers of grit. Well-marked examples are seen in the fine ledges on the north side of the railroad east of Newton Center (Boston V, U 1–2). An ill-defined case of cross-bedding occurs in the lens at Thompsonville (Figure 4, A). Other occurrences are found in the sandstones that accompany the conglomerate and slate in the railroad cut south of Chestnut Hill Reservoir (Boston VI, C 1), in the sandstone and melaphyr ledges at Brighton (Boston V, I 28), in the sandstone and slate outcrops at Roslindale (Boston VI, I 20), in the conglomerate and sandstone ledges by the Neponset River at Mattapan (Boston VI, W 28) and in the fine ledges in Melville Garden at Hingham (Boston Bay VI, G 32). The distribution of these examples indicates that cross-bedding is not a characteristic of any particular portion of the basin, but that it is, on the whole, equally distributed among the sandstones and grits throughout the basin. At all of the outcrops named the cross-bedding appears merely as a subordinate feature.

——:—*Ripple-marks.* Ripple-marks have been found in association with some of the cross-bedded lenses above mentioned, as indicated in Figure 4, A. More commonly, however, they occur in connection with finer, more shaly sandstones. Only six cases have been observed. Perhaps the best example is to be found in the quarry on Warren Street in Brighton (Boston V, G 28). There the ripple-marks occur in fine sandstone, are sharply defined and appear in normal position on surfaces that dip gently north. A little less than a quarter of a mile to the east there is a fine ledge of somewhat shaly sandstone cut by a large mass of melaphyr. On the northeast side of this ledge rather indefinite forms occur which appear to be ripple-marks in an inverted position. The layers exposed seem to present the casts of the marks rather than the marks themselves. The apparent inversion

in this case may doubtless be explained as an accompaniment of the intrusion of the neighboring melaphyr. Other instances of ripple-marking may be seen along the railroad east of Newton Center (Boston III, V 2), in the ledges on the south side of Forest Hills Cemetery (Boston VI, R 18) and at Milton Lower Mills (Boston VI, XY, 25–26). Ripple-marks as well as cross-bedding seem to be generally distributed rather than confined to any particular region, and to form only subordinate features of the ledges in which they occur. Mud-cracks have been seen in only one locality, the ledge at Forest Hills Cemetery just mentioned. No raindrop impressions, footprints or other organic markings on the surfaces of the rock layers have been observed. It may be said, however, that vague trails and impressions occur in the Somerville and Neponset slates and have been described by Woodworth (a, p. 127–128). Burr's discovery of indefinite casts of tree-trunks in the sandstone and grit of the Forest Hills locality has been mentioned on page 100. One such form was seen there by the writer.

——:—*Local Unconformities.* No actual examples of local unconformity have been observed in the Boston Basin but there is some evidence of contemporaneous erosion of the sediments during their deposition. Pebbles of conglomerate, grit, and sandstone, of the same composition and texture as the corresponding rocks of the conglomerate series, occur in the conglomerate at several places. Eleven such instances have been noted, as follows: Medford (Boston IV, N 31–32), West Newton (Boston II, K 29 and G 35), Newton Center (Boston III, U 1–2), Brighton (Boston V, H 26), Brookline (Boston VI, A 6 and C 1), Jamaica Plain (Boston VI, L 9 and M 14), Hyde Park (Boston VI, L 30–31), and Hough's Neck (Boston Bay III, J 30). As in the case of cross-bedding and ripple-marks the contemporaneous erosion is not limited to particular areas but appears to have occurred generally throughout the basin, though not on an extensive scale. Certainly such contemporaneous erosion must mean local unconformities somewhere. Perhaps more diligent examination of existing outcrops or future exposure of ledges now covered may bring some examples to light.

Relations to Subjacent Rocks. At several places in the Boston Basin the relations of the conglomerate series to the subjacent rocks are clearly shown. In Medford, according to LaForge, the conglomerate grades into arkose which rests against its parent granite (LaForge p. 89). Similar phenomena are seen at East Dedham. In Hyde Park and South Natick the conglomerate becomes increasingly felsitic

as felsite areas are approached, so that no sharp lines of division can be drawn between conglomerate and felsite breccia or between the latter and true felsite. At Nantasket the ledges on the east side of Weir River near its mouth (Boston Bay VI, PQ 29) show conglomerate resting on granite. The conglomerate here might more properly be called a breccia but it shades upward with no well-marked line of separation into true conglomerate. The materials of the lower or breccia zone are largely granitic, similar to the underlying granite and felsite. The finer fragmentary material has been deposited in cracks in the granite, while larger masses are numerous in the debris

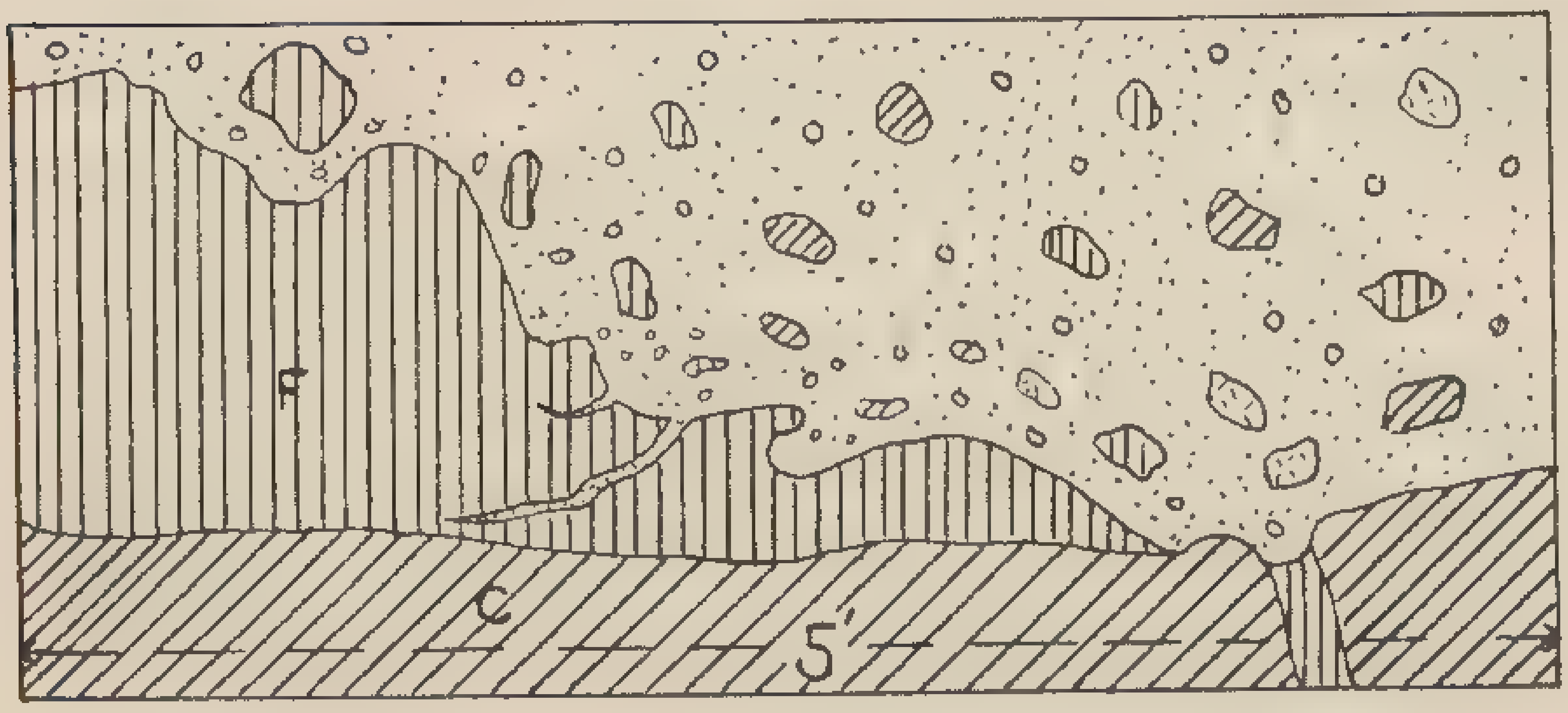

Fig. 5.— A. Contact of conglomerate and granite at Nantasket (slightly modified from Crosby, III, p. 142).
B. Conglomerate resting on fine (F) and coarse (C) granite (Boston Bay VI, P 29).

above the contact. This area has been described by Crosby, who states that the presence of felsite and melaphyr among the granitic debris indicates that the conglomerate at this point is not really basal

but is probably a case of overlap (k, p. 77). The relations of the conglomerate to the granite at this point are shown in Figure 5. Similar phenomena at Hingham are described by Crosby. The contact area lies in a field south of Hockley Lane, bounded on the north by melaphyr and on the east and south by granite. The relations of the conglomerate and granite are very intimate. The conglomerate is made up largely of angular and half-rounded debris of the same coarse red granite and of fragments which range from single grains of quartz and feldspar to masses two feet or more in diameter, sometimes only imperfectly separated from the parent ledge, the finer sediment appearing to penetrate the cracks in the granite (l, p. 215).

In none of the cases mentioned is there an appearance of anything like boulder-clay at the contact with the underlying rock. The underlying surface does not seem to have been smoothed, polished, nor striated. These features, so common in our glaciated regions of the present day, are entirely absent. Instead the underlying surface bears evidence of deep disintegration under atmospheric agencies and of rearrangement and deposition of the loosened material in close proximity to its parent ledges.

Summary of the Roxbury Series. (1) Arkose occurs in several localities along the border.

(2) Conglomerate occurs in three broad, nearly east-west areas separated by bands of slate. The conglomerate areas narrow eastward and disappear, while the slate areas broaden and appear to merge in the same direction.

(3) Melaphyr occurs in several isolated areas as contemporaneous intrusions or flows.

(4) The coarse conglomerate occupies an axial position in the great conglomerate areas but varies greatly in texture in neighboring outcrops. The rock becomes finer from west to east and from north or south toward the slate areas; but the decrease in coarseness consists rather in a change of the relative proportions of gritty or sandy material in the rock than in a difference in size of the pebbles; large pebbles occur in rocks that are chiefly grit.

(5) Bedding is best developed toward the borders of the conglomerate areas. Banding is the prevalent type, the frequency of occurrence increasing as the slate areas are approached.

(6) Lenses and streaks are of relatively infrequent occurrence. The former tend to appear as separated individuals in the same horizon or in parallel horizons rather than in linear bundles or imbricated masses.

(7) Cross-bedding is not common. The few examples noted are widely scattered rather than limited to a particular region.

(8) Ripple-marks and sun-cracks are also relatively rare but similar to cross-bedding in distribution. The ripple-marked layers, with perhaps a single exception, are in their normal position and are not inverted. No definite organic markings have been observed.

(9) No actual examples of local unconformity have been seen but contemporaneous erosion is indicated by the inclusion of representatives of the series as pebbles in the conglomerate. The distribution of these pebbles shows that this feature is not confined to any particular region.

(10) The series appears to rest on an old land surface that had been deeply disintegrated by atmospheric agencies. No polished nor striated surfaces indicative of ancient glacial erosion were observed.

THE NORFOLK BASIN SERIES.—*Distribution:* — *Arkose.* The known areas of arkose in the Norfolk Basin are confined to the exposures at Pondville in the southwest part of the field.

——:—*Conglomerate.* Conglomerate occurs in an apparently continuous zone about half a mile wide along the south slope of the Blue Hill Range, from the Neponset River eastward to Great Pond in Braintree, and in more or less separated areas from Walpole southwest toward Pondville.

——:—*Sandstone.* South of the conglomerate zone an area of sandstone stretches east and west between the same limits and extends south as far as the railway cut about a mile north of the station at Canton Junction. Southwestward sandstone occurs in connection with the conglomerate in the manner above indicated.

——:—*Slate.* Slate or shale is not a conspicuous member of the series in the northeast part of the basin. It occurs toward the southern border of the sandstone area interlaminated and interbedded with the sandstone. The best exposure is found in the railway cut north of Canton Junction. Southwestward the slate assumes practically equal importance with the conglomerate and sandstone and occurs in connection with them. The best exposure of the series in this region is at Pondville (Franklin VIII, K 29).

——:—*Limestone.* Limestone occurs at a single locality, the railway cut north of Canton Junction. A small lenticular mass 1.5 feet thick is interbedded with red sandstone and slate (Woodworth, b, p. 147).

——:— *Associated Igneous Rocks.* Igneous rocks are of little importance in the Norfolk Basin. The dike in the railway cut north

of Canton Junction and the impregnations of the conglomerate referred to in the previous chapter are the only known exposures. The field, however, is thickly covered with glacial material and it may well be that many important occurrences lie hidden.

Texture of the Conglomerate. Variations in the texture of the conglomerate in the northeastern part of the basin are best seen in the rocky ridge east of the Neponset River (Dedham IV, southward from I 22). At the northern end the conglomerate is very coarse. Subangular pebbles eight or ten inches in diameter are numerous and boulders more than two feet long are not uncommon. Southward the conglomerate grades through various alternations into grit and shaly sandstone. Farther east similar coarse conglomerate occurs on the south side of Houghton Pond, on the south slope of Bear Hill, at ledges three-quarters of a mile farther east along the Monatiquot Stream, and in large broken masses at the northwest end of Great Pond. In each of these cases grit and sandstone appear to the south but no gradation is observed.

In the southwestern part of the basin the coarsest conglomerate occurs about half way between Walpole and Pondville (Franklin VIII, R S 20–21). There the pebbles of the conglomerate sometimes exceed one foot in diameter but the rock as a whole cannot be said to be so coarse as the conglomerate above described. At this locality the pebbles become larger toward the south but the gradation is not so marked as in the other case. At Pondville (Franklin VIII, K 29) the conglomerate associated with the finer sediments is relatively fine and the pebbles consist of white quartz. Neighboring ledges of conglomerate extend northwest from M 30 to L 29. At the south these ledges consist of fairly coarse conglomerate of the normal type, with pebbles five inches or more in diameter, but northwestward the latter becomes finer and alternates with sandstone and slate. Thus in a general way the direction of gradation in texture in the southwestern part of the basin is opposite to that of the northeastern portion.

As in the Boston Basin the smaller pebbles attain the greatest degree of rotundity but even these can seldom be described as well rounded. They are more properly termed subangular or rounded.

Bedding.—As in the case of the Boston Basin the bedding is best displayed where the finer sediments occur. Satisfactory determinations are often not easily obtained. Nevertheless the proportion of the outcrops observed that display features of bedding is greater in the Norfolk Basin than in the Boston Basin. Many boulders and large masses of the sedimentary rocks not certainly in place

have been studied but have not been included in the following enumeration. They are entirely similar to the masses more certainly *in situ* and it is believed that their exclusion will not materially modify the proportions given.

——:—*Bands.* In the Norfolk Basin banding is again the prevalent type of bedding. Of the thirty-six outcrops recorded in the writer's field notes twenty-three exhibit some degree of banding. The areas where these features occur are not confined to any particular region but are generally well distributed throughout the basin. In some cases the banding is well defined and the several types of sediment are clearly bedded with no transition between coarser and finer materials. Such a condition is seen in some parts of the ledge southeast of Norwood (Dedham, I, X 32) where slate and conglomerate with pebbles one or two inches in diameter sometimes occur together with no gritty nor slaty bands between. In other cases the banding is very indefinite and irregular so that no sharp line of division can be drawn between the neighboring types and the attitude of the band can be determined only by its general appearance in the ledge. Sometimes the indefinite bands are narrow and may become mere streaks. The latter are, however, not abundant; only two or three cases have been noted.

——:—*Lenses.* The occurrence of lenses in the Norfolk Basin has been observed in only four localities: in the gritty portion of the rocky ridge east of the Neponset River (Dedham IV, I J 25), in sandstone ledges in approximately the same strike east of Ponkapoag Pond (Dedham IV, Y 25), in the large masses of coarse conglomerate not certainly in place south of Bear Hill (Dedham VII, E F 18), and half a mile east of the last locality (Dedham VII, G 19). In all cases they are composed of red sandstone and are so small that little can be determined with reference to their arrangement.

——:—*Cross-bedding.* Cross-bedding is even less common than lenticular arrangement. Only three cases have been observed and these are found toward the southern end of the rocky ridge above mentioned and in the large separated masses or ledges of sandstone at the northwest end of Great Pond. The best example occurs at the ledges on Pecunit Street in Canton (Dedham IV, I J 25).

——:—*Ripple-marks and Mud-cracks.* Ripple-marks and mud-cracks have been observed at only one locality, the Pecunit Street ledges above mentioned. They are well exposed and show that the strata are not inverted. No traces of organic forms were seen on these surfaces but farther north in the same ridge, and farther south in the ledges at Pondville, traces of tree trunks or roots have been found, while in the

railway cut near Canton Junction actual plant stems have been recovered, as noted on page 101.

——:—*Local Unconformities.* No cases of local unconformity have been seen by the writer in the Norfolk Basin. There is however some evidence of contemporaneous erosion here as in the Boston Basin. Occasional pebbles of sandstone and grit similar to the sediments of the basin are inclosed in the conglomerate. An instance of this kind is found in the exposures south of Bear Hill (Dedham VII, E F 18).

Relations to Subjacent Rocks. The coarse conglomerate along the south side of the Blue Hill Range is believed by Crosby to be the basal member of the series and to rest in sedimentary contact against the crystallines of the Blue Hills region (n, p. 477). There is however some reason for questioning this view. The discussion of the evidence for and against Crosby's idea is reserved for the following chapter. At Pondville the basal strata are unquestionably exposed. Arkose, overlaid by slate, sandstone, and quartz-pebble conglomerate, rests against the granite from which it was derived. The actual contact of the arkose with the granite is not seen but the arkose is so evidently the recomposed debris of the granite that there can be no doubt that the latter forms the floor on which the former was deposited. The formation of the arkose and of the quartz-pebble conglomerate above indicate a long period of subaerial disintegration of the land from which these materials were derived.

Little or no resemblance is to be seen between the rocks exposed near the granite at Pondville and the glacial accumulations of the Great Ice Age. Since the actual contact is not exposed it cannot be determined by direct observation whether polished and striated surfaces underlie the arkose but the presence of the latter and the overlying stratified deposits, both entirely unlike ordinary till, render any such supposition untenable. Similarly there is no evidence that striated surfaces underlie the conglomerate along the south side of the Blue Hills.

Summary of the Norfolk Basin Series. (1) In the northeastern part of the basin the conglomerate lies along the northern border of the sediments. In the southwestern part conglomerate appears in most of the localities where the sediments are exposed.

(2) Igneous rocks, so far as their occurrence is known, are subordinate features.

(3) In the northeastern part of the basin the gradation in texture of the series from coarse to fine is well marked from north to south. In the southwestern part a less well-defined gradation in the opposite direction occurs.

(4) Banding is the prevalent type of bedding and is displayed in some form in most of the outcrops.

(5) Lenses are not common and no definite arrangement of them has been observed.

(6) Cross-bedding, ripple-marks, and mud-cracks are relatively rare. They indicate that the strata have not been inverted.

(7) Contemporaneous erosion during deposition is indicated by the inclusion of portions of the sediments as pebbles in the conglomerate.

(8) The sediments were deposited on a surface long exposed to subaerial disintegration. There is no evidence of ancient glacial scoring.

THE NARRAGANSETT BASIN SERIES. — *Distribution:* — *Arkose.* Areas of arkose occur at several places along the border of the Narragansett Basin. Exposures are found near Fall River, along the east shore of Narragansett Bay south of Tiverton, at Sachuest Neck, along the western border of the basin from Natick into Cranston, and on some of the islands in the bay. In some localities, as at Steep Brook (near Fall River), it does not appear to be actually the basal member of the series (Foerste, b, p. 269) but in all the cases noted it forms one of the basal members. According to Shaler the arkose is irregularly distributed in patches rather than in extended masses following an ancient shore line (Shaler et al., p. 53).

——: —*Conglomerate.* Conglomerate occurs at varying horizons in the series from the base to the top but coarse conglomerates form the upper members. The latter rock in the northern part of the basin is confined to somewhat elongated synclinal areas extending east-northeast. The principal exposures are at Attleboro, Somerset, Dighton, and Swansea, Mass. (Woodworth, d, p. 184–185). The coarse conglomerate at Seekonk (Providence VIII, G 18) resembles that at Attleboro and Dighton and may perhaps be correlated with the lower member of the Dighton group (ibid., p. 174). In the southern part of the basin coarse conglomerates occur again at Purgatory, Paradise Rocks, and Miantonomy Hill near Newport.

——: — *Sandstone.* Sandstone accompanies the coarser and finer sediments at varying horizons. It does not form masses extensive enough to be correlated and mapped as units but it is interbedded with other sediments in each of the major groups of the series. The sandstone presents several facies. An important and interesting member known as the Attleboro sandstone is well exposed west of the water tower in North Attleboro and again south of Goat Rock and north of

Hoppin Hill. The rock is massive and fine grained, varying from green to brown in color. The massive structure and the angularity of the particles of quartz and feldspar seen under the microscope make it likely that it is to be regarded as an ash deposit accompanying the felsite flows of the northwest corner of the basin (Woodworth, d, p. 151). Another more normal type is well exposed at the Thatcher Road bridge a mile south-southwest of the Attleboro station. About forty feet of coarse gray, conglomeratic sandstone are exposed in a fine glaciated ledge above the railroad. Farther north, at Sheldonville, and eastward, the sandstones are deeply colored red.

——:—*Shale.* Shales form a large proportion of the Carboniferous series in the Narragansett Basin. They occur in varying horizons but are most conspicuous in the middle group or the Coal Measures. They are frequently carbonaceous and fossiliferous and are accompanied at many localities by beds of coal. They are widely distributed throughout the basin but assume greater importance toward the southern part.

——:—*Limestone.* Two occurrences of limestone are known in the Narragansett Basin. The main exposure is found at the south base of the hill occupied by the town of South Attleboro. Only six feet of sediments appear in the section. The limestone occupies irregular kidney-shaped cavities or is found in rude layers or isolated nodular masses one-half inch in diameter, frequently elongated parallel to the strike, and lies stratigraphically low in the red series. The other occurrence is at North Attleboro, where the rock is entirely similar in character and mode of occurrence. In both cases the limestone is evidently of secondary origin and resembles that of the Norfolk Basin (Woodworth, d, p. 149–150).

——:—*Associated Igneous Rocks.* In the northwestern part of the basin near North Attleboro contemporaneous acid volcanic rocks accompany the Carboniferous sediments. The mutual relations of volcanics and sediments are discussed in the succeeding chapter.

Texture of the Conglomerate. Variations in the texture of the conglomerate occur both vertically and horizontally. The coarsest conglomerate lies at the top of the series and is preserved only in synclinal areas. At the junction of Thatcher and County Roads in Attleboro, and half a mile south, the upper conglomerate is well exposed. The pebbles attain the size of six or eight inches. Farther south, at Purgatory and the Paradise Rocks near Newport, the conglomerate is much coarser, indicating a gradation in texture in that direction.

The relation of shape to size, in the case of the pebbles, is not so

clearly shown in the coarse conglomerate of the Narragansett Basin as in the other basins. The large pebbles at Purgatory have been so distorted that their original shape is not well seen. From their present appearance, however, it may be inferred that they were originally subangular to rounded. Thus it is probably true in this basin as in the others that the larger pebbles are more irregular in shape than the smaller pebbles.

Bedding. The writer's observations in the Narragansett Basin have not been sufficiently numerous to furnish numerical data with reference to the features of bedding. The evidence at hand, however, goes to show that the bedding is ordinarily well indicated, except in the case of the coarsest conglomerates.

——: —*Bands.* Banding is again the prevalent type of bedding and displays in general the characteristics noted in the Boston and Norfolk Basins. In the coarser textured rocks it is likely to be more or less indefinite with a tendency to the development of streaks. In the finer sediments the bands are usually well defined.

——: — *Lenses.* Lenses are of relatively infrequent occurrence. They present the same characteristics already noted in the Boston and Norfolk Basins.

——: — *Cross-bedding.* Cross-bedding occurs in some of the sandstones and grits but only occasionally. The best example known to the writer is found in the ledges at the Thatcher Road bridge south of the Attleboro station. There both banding and cross-bedding are beautifully exhibited on the natural polished surface of the ledge. The attitude of the cross-bedding indicates that the upper surface of the beds is on the north.

——: — *Ripple-marks.* Some of the finer sediments have ripple-marked surfaces which bear organic markings or the imprints of raindrops. At the quarry half a mile south of the junction of Thatcher and County Roads in Attleboro an excellent exposure of micaceous shaly sandstone displays all these features. The ripple-marked surfaces, now nearly vertical, are marked with raindrop impressions, worm-trails, and rush-like imprints of stems or leaves. In the railway cut a mile north-northeast of the station at Perrins in Seekonk the dark gray, micaceous, shaly sandstone bears obscure casts, possibly of organic origin, while in the same section more carbonaceous and shaly layers contain plant stems.

——: — *Local Unconformities.* Local unconformities, inferred in the other basins from evidence derived from the pebbles, are clearly exhibited in some parts of the Narragansett Basin. The ledge at Thatcher

Road bridge in Attleboro shows two or three fine examples that have been described and figured by Woodworth (d, p. 176–177). A bed of fine sandstone twenty feet thick has been excavated to the underlying coarse pebbly beds and then the eroded area covered with coarse sands. A few yards farther north another exposure by the roadside shows erosion following the deposition of red shale and preceding the deposition of gray beds. Fragments of the red shale are included in the overlying gray sediments.

Relations to Subjacent Rocks. The contact of the Carboniferous sediments with the underlying rocks is seen at several places along the border. On the western side of the basin two and one-half miles north of Natick, R. I., the basal beds rest upon the Precarboniferous terrane. They contain many angular fragments and rounded pebbles derived from the older rocks, the material of the pebbles varying with the character of the underlying floor (Foerste, b, p. 253). On the eastern side of the basin at Tiverton the contact between the granite and the overlying Carboniferous rocks is well shown. The clastics consist of interbedded arkoses and coaly shales, sometimes one and sometimes the other in contact with the granite (ibid., p. 272). Where arkose occurs along the border it is generally found near those places where the immediately underlying rocks consist chiefly of granite (ibid., p. 375). The arkose and the basal conglomerate show that the Precarboniferous rocks were subjected to protracted subaerial disintegration before the deposition of the sediments.

No polished nor striated surfaces nor other evidences of ancient glacial conditions are exhibited by the various observed contacts.

Summary of the Narragansett Basin Series. (1) Conglomerates, sandstones, and shales, with some coal beds, occur interbedded at various horizons, but the coarse conglomerates occur at the top of the series and are confined to elongated synclinal areas.

(2) Contemporaneous acid volcanic rocks are associated with the series.

(3) The upper conglomerate becomes coarser toward the south.

(4) Banding is the prevalent type of bedding.

(5) Lenses are relatively uncommon and present the same characteristics noted in the Boston and Norfolk Basins.

(6) Cross-bedding and ripple-marked surfaces occur occasionally. They show that the strata are not inverted.

(7) Two well-defined examples of local unconformity appear at Attleboro.

(8) The sediments were deposited on a terrane deeply disintegrated by subaerial agents. There is no evidence of ancient glacial scoring.

THE HARVARD CONGLOMERATE.— *Distribution.* The Harvard Conglomerate occupies only a limited area near the town of Harvard, Mass. The best exposures are found on the top of the hill about half a mile north of the center of the town. Sandstone and grit are interbedded with the conglomerate, which on the north is overlaid apparently conformably by phyllite. No igneous rocks appear to be associated with the series.

Texture of the Conglomerate. No definite gradation in texture was seen, and no definite relation between the size and shape of the pebbles was observed. Large and small pebbles alike were angular or subangular.

Bedding. The bedding of the conglomerate and sandstone is of the banded type. No lenses, cross-bedding, ripple-marks nor local unconformities were noted.

Relations to Subjacent Rocks. No definite data with regard to the relations of the conglomerate to the subjacent rocks are at hand save Burbank's statement that it is "interstratified with the enclosing gneiss" (p. 224–225). No indications of ancient glaciated surfaces are to be found.

GENERAL SUMMARY.— (1) In each of the three basins arkose occurs at certain places along the border but it does not appear in the Harvard Conglomerate.

(2) Conglomerate occurs in all three basins, interstratified with finer sediments. The same relation is seen at Harvard.

(3) Contemporaneous igneous rocks occur in all three basins but not at Harvard. They attain greatest importance in the Boston Basin.

(4) The conglomerate in the Boston Basin grades into finer rock north, east, and south. In the Norfolk Basin the gradation from coarse to fine is from north to south in the northeastern part and less distinctly in the opposite direction in the southwestern part. In the Narragansett Basin the conglomerate becomes coarser toward the south. In the Boston Basin the decrease in coarseness consists mainly in a change in the relative proportions of gritty or sandy materials in the rock rather than in a difference in the size of the pebbles. In the other basins this feature is not so clearly shown. No direction of gradation was observed in the Harvard Conglomerate.

(5) Bedding is not well developed in the coarsest conglomerates but is better shown where the finer sediments appear. Banding is the prevalent type.

(6) Lenses are of relatively infrequent occurrence and tend to be

grouped in the same horizon or in parallel horizons rather than in interwoven bundles.

(7) Cross-bedding is not a common feature but it occurs in all three basins. It has not been observed at Harvard.

(8) Isolated occurrences of ripple-marks, found in each basin, show no inversion of the strata, except possibly in a single case at Brighton, where the apparent inversion may perhaps be due to the neighboring igneous intrusion. No ripple-marks were seen at Harvard.

(9) Evidence of contemporaneous erosion is found in all three basins and in the Narragansett Basin well-marked examples of local unconformity occur. No evidence of this character has been found at Harvard.

(10) The sediments in all three basins were deposited on an old surface long subjected to the agents of subaerial disintegration. There is no evidence of ancient glacial scoring. The relations at Harvard are not clear but no evidence of ancient glaciation has been observed.

Structure of the Conglomerates.

The Boston Basin.—*Literature.* Although limited in area, the Boston Basin has been made the subject of a considerable literature, chiefly, however, in the form of short papers referring to specific features of the basin, or longer papers of broader scope, in which the features of the basin are mentioned only incidentally. The Danas (1818) speak of the petrographic character of the graywacke; they note the size of the ingredients, from rolled masses to grains of sand, the relative abundance of quartz and petrosilex, and the less frequent occurrence of porphyry, argillite, and "sienite." They also speak of the character of the cement as consisting not of argillite but of graywacke, often so fine in grain as to appear homogeneous. President Hitchcock (1833) states that the argillaceous slate in the vicinity of Boston is intimately associated with the graywacke and probably ought to be considered as a variety of that rock. He includes the melaphyrs with the graywacke. In 1856 W. B. Rogers announced the discovery of *Paradoxides harlani* Green at Braintree.

In the early sixties the controversy as to the nature and origin of certain pebbles in the conglomerate arose. President Hitchcock, supported by his son, C. H. Hitchcock, from studies at Newport, R. I., and at localities in Vermont, contended that the rocks in these places show different stages in metamorphism whereby conglomerates and

allied rocks may be changed to gneisses and schists by pressure, the rocks becoming plastic. These views were vigorously opposed by Jackson and Rogers, who argued that the so-called distorted pebbles were only water-worn joint-blocks. The same contest was still continued as late as 1880 by Crosby and Wadsworth, the former claiming that at certain ledges in Brighton the pebbles showed signs of deformation while in a state of plasticity induced by pressure, while the latter asserted that the features noted were produced by the glaciation of the water-worn pebbles exposed at the surface of the ledges.

Papers by Hunt in 1870 refer to the sediments of the Boston Basin only in a general way. A few years later Dodge contributed two important but brief papers on the geology of Eastern Massachusetts. Shaler has written several short papers, notably an account of the slate exposed in the floor of the Chestnut Hill Reservoir and its relations to the overlying conglomerate and a short paper describing the Boston and Narragansett Bays as overlapping synclinal troughs, faulted down longitudinally and transversely. In his later monograph on the Narragansett Basin the same writer includes certain features of the Boston Basin in connection with his treatment of the Rhode Island sediments.

The most extended and detailed studies of the Boston Basin have been made by Crosby, who has written a series of lengthy papers which will be referred to later. Briefer papers announcing the discovery of fossils and discussing the structure of the Newton-Brookline-Brighton area have been published more recently by Burr.

The igneous rocks of the basin have been discussed by a number of writers, including Wadsworth, who gives an extended bibliography of the geology, mineralogy, and petrography of the basin up to 1877, Crosby, Benton, Davis, Williams, Diller, Wolff, Miss Bascom, Hobbs, Wilson, and Burr.

Early Views of Crosby. Before the announcement by Wadsworth, in 1881, that the Paradoxides slates of Braintree are invaded by granite there was much difference of opinion as to the relation of the slates to the conglomerates. The question is still open as regards the rocks of the Boston Basin proper. In his earlier work (1880) Crosby maintained that all the slate is of the same age, Cambrian, as indicated by the Paradoxides beds at Braintree, and that the conglomerate underlies the slate conformably and grades upward into it (b, p. 186). In opposition to the view that pebbles of slate occur in the conglomerate, he maintained that such is not the case, but that the so-called pebbles are either contemporaneous deposits of lenses or pockets of slate in

the conglomerate, or else decomposed pebbles of felsite or petrosilex (ibid., p. 189–190). The melaphyr or amygdaloid he regarded as largely of sedimentary origin and as underlying the conglomerate. According to his view the rocks of the basin were thrown into a series of anticlinal and synclinal folds with numerous faults, the whole pitching eastward; the conglomerate became coarser toward the base and the underlying amygdaloid was exposed in the axes of the synclinals.

Later Views. With the discovery of Wadsworth that the slates of Braintree are cut by granite it became necessary to regard the conglomerate as more recent than some, at least, of the slate, for pebbles of granite occur in the conglomerate. The contention of Crosby that the conglomerate underlies all of the slate could no longer be sustained. In his later papers he still maintains that the conglomerate passes conformably upward into slate, but that there are two slates of different ages. With this view it may be said that most geologists agree. The occurrence of slate pebbles in the conglomerate is now admitted by Crosby. The work of Benton and others has shown that the amygdaloid is a true igneous rock and cannot be regarded as sedimentary. Moreover, it has been shown by Burr (b, p. 64) that the position of the amygdaloid cannot be regarded as inferior to the conglomerate but that it occurs at varying horizons and is not confined to anticlinal axes. The main structural features of the basin as outlined by Crosby in his earlier report are still believed to be correct but certain modifications have been necessary, which will appear in the more detailed account of the structure that is to follow. The southern and southeastern portions of the basin have more recently been worked out in considerable detail by Crosby and his results have been largely employed in the present discussion of those areas.

General Structure:—The Northern Boundary. The relative straightness and uniformity of the escarpment from Malden to Waltham has already been mentioned. In only one place is there an important interruption. At Medford a small area of conglomerate lies north of the Somerville slate and rests against the northern crystallines. The escarpment weakens at this point. The relations of this conglomerate to the neighboring slates are somewhat uncertain, because no satisfactory dip has been obtained. According to Crosby the conglomerate has a southerly dip and is overlaid conformably by quartzite or sandstone. This seems to be the general view (Crosby, g, p. 16; LaForge, p. 74–76). Thus the conglomerate would appear to pass beneath the slates and to be continuous with the conglomerate south of the Charles

River. This is the view held by LaForge. A somewhat similar view is held by Crosby, except that the latter believes that the continuity of the conglomerate is interrupted by a fault, with downthrow on the south along the smooth escarpment (Crosby, g, p, 21). In his discussion of the probability of a boundary fault LaForge (p. 89) presents two facts that militate, as he thinks, against the hypothesis. First, the great Medford dike extends from the sedimentary rocks of Somerville well into the igneous highlands without evidence of being faulted. Second, the conglomerate and arkose of West Medford appear to pass into the granite next to which they occur without evidence of faulting. As regards the first objection it may be said that though no direct evidence of the faulting of the dike is at hand it is by no means certain that no faulting has occurred. The dike cannot be traced by continuous outcrops from Somerville into Medford; furthermore, it is crossed by the valley of the Mystic just south of the escarpment. But, even if the dike is not faulted, it cannot be assumed that the escarpment does not represent a fault, for if the dike were younger than the period of faulting, which is not unlikely, it might readily pass across the previously formed fault plane without itself becoming faulted, though in that case branches of the dike might be expected to traverse the fault for a certain distance in either direction. The second objection does not hold, for the conglomerate and arkose might be supposed to represent a remnant preserved in a depression of the crystallines and uplifted with them by the faulting, so that the upper members of the series were carried above the level of erosion. According to LaForge's view the escarpment forms an old shore line against which the slates and conglomerates were deposited (p. 90). This is indeed the narrow terrane view. The relations of the rocks in the Boston and adjoining basins seem to warrant the supposition that the area of deposition was far more extensive and that dislocations subsequently occurred on so large a scale as to justify the hypothesis of a fault of the dimensions required by the appearance of the escarpment. The present topographic form is probably the result of differential erosion and does not in itself express displacement. Thus from the above discussion it appears that while it is true that no conclusive evidence has been adduced in favor of the boundary fault hypothesis it is also true that no valid arguments have been advanced against it.

——: —*The Somerville-Cambridge Slate.* According to LaForge (p. 38–39) the slates of Somerville and Cambridge are generally considered as forming a great syncline, the axis of which runs along the valley

of the Charles River between Cambridge and Brighton. The Somerville portion, though locally much folded (ibid., p. 77), is, on the whole, tilted southward. It is matched on the south side of the Charles River by a band of slate or mixed slate and conglomerate, varying in width and dipping north and overlying a great mass of northward dipping conglomerate. According to this view the Medford conglomerate underlies the slate and rises from beneath it. The northern outcrops of the slate are stratigraphically older and lower than the southern outcrops and are more arenaceous. The structure of the eastern portion of the Somerville area is a relatively simple monocline with a low southerly dip. The western portion, however, is much more complicated and appears to consist of an assemblage of folds not sufficiently exposed for correlation (ibid., p. 38–39). An anticlinal axis with a northeast-southwest trend is believed to pass beneath Meetinghouse Hill in Watertown. This has been represented in the accompanying section (Plate 6). Assuming an average dip of 20° for the northern limb of the great syncline, the thickness of the slates in Somerville may attain the maximum of 2,300 feet. A well-boring in Cambridgeport which does not pass entirely through the slate shows the latter to be at least 900 feet in thickness (ibid., p. 77).

On the south slope of College Hill in Somerville (ibid., p. 25), there is a limited outcrop of quartzite. Similar rocks occur at Everett and East Chelsea, though the identity of these quartzites has not been established. In Somerville the quartzite lies in the axis of a pinched syncline. It is not known whether these beds overlie or come within the Somerville slate but no stratigraphically higher rocks are seen overlying the quartzite in any of these localities. At Malden (ibid., p. 70–72), along the railroad between Faulkner and Maplewood, cross-bedded slates occur with a northwesterly dip of 55°–90°. The indications from the cross-bedding are that the strata have been overturned toward the southeast.

The age of the slates has never been satisfactorily determined. They are probably either Carboniferous or Cambrian. The argument for their Cambrian age is set forth by LaForge (ibid., p. 81–82) as follows: —

(a) They are lithologically similar to the recognized Cambrian slates of the region.

(b) They are lithologically similar to the slate at Hyde Park, which, though of undetermined age, is certainly older than the conglomerate, since it is cut by granite, pebbles of which occur in the conglomerate.

(c) They are cut in one or two places by intrusions which are

apparently part of the felsite period of eruption and felsite pebbles are found in the conglomerate.

(d) It is inconceivable that so great a thickness of unfossiliferous sediments could be formed well into Carboniferous times.

(e) Indefinite forms, possibly organic, have been found in the slates and these present Cambrian rather than Carboniferous facies.

(f) The whole thickness of slate exposed in Somerville is capped or overlaid by quartzite,— a feature unique in the Carboniferous of New England but common in the Cambrian formations.

The argument for the Carboniferous age of the slates is thus outlined by the same writer (ibid., p. 82–84):—

(a) The originally highly carbonaceous character of the slates.

(b) The commonly accepted view of the structure.

(c) Their lithological similarity to the slate interbedded with the conglomerate.

(d) Their comparatively fresh, unaltered and unmetamorphosed condition. The known Cambrian areas are affected by dynamic and contact metamorphism.

(e) The similarity of the igneous rocks north and south of the basin points to their former continuity, the excavation of the basin, and the deposition of the included sediments.

(f) The inclusion-bearing dike in the Mystic quarry contains fragments of andesitic breccia quite like the breccia outcropping in Malden. The latter are Postcambrian.

(g) The long line of exposures parallel to the line of the crystalline boundary shows only two doubtful cases of any intrusive rocks which appear to belong with any of the igneous rocks of the escarpment. On both sides of the slate in Medford and in Brighton occur conglomerates containing pebbles of these igneous rocks and the contacts are probably sedimentary.

Perhaps the strongest argument for the Cambrian age of the slates is their resemblance to the known Cambrian rocks of the region and their marked dissimilarity to the known Carboniferous rocks of neighboring areas, especially to the rocks of the Narragansett Basin. The intrusion of the slates by felsitic rocks, if definitely proved, would be a strong argument for the Precarboniferous age of the former, if such intrusion can be shown to be definitely felsitic or granitic, and infrequency of occurrence need not necessarily weigh against the argument. The base of the slates is not certainly exposed. Intrusions penetrating only the lower portion of the slates may exist without having as yet been discovered. Perhaps some of the numerous quartz veins

by which the formation is cut may represent the upward extension of such intrusions, since the latter are commonly believed to be attended by silicated solutions.

The most serious difficulty in the assumption of Cambrian age is the question of structure. Two hypotheses may be suggested. First, the pinched syncline at College Hill, the apparently overturned syncline at Malden, and the overthrusting shown in the vicinity of Chestnut Hill suggest that the strata from that point northward may be inverted and that the older Cambrian strata may thus be brought to the surface. A second hypothesis is that a fault with upthrow toward the north occurs along the northern border of the conglomerate area from Brighton toward Auburndale. Such a fault could easily escape recognition on account of the relative weakness of the rocks on either side and the heavy drift covering. Evidences of such a fault are not entirely wanting. The long conglomerate ledge by the railroad track at West Newton shows intense shearing; the pebbles of the conglomerate are elongated and cracked and the front of the ledge rises in a straight and smooth escarpment suggestive of faulting. At Auburndale, half a mile east of the railroad station and a few rods south of the tracks, conglomerate with interbedded slate is found dipping 85° SE, and the pebbles are highly sheared. Such a dip is unusual along the northern border of the conglomerate and suggests drag. On the supposition that the slates are upthrown by faulting, the northern crystallines must be assumed to be down-faulted along the Malden and Waltham escarpment so that the slates are brought into opposition with the Medford conglomerates.

As regards the first hypothesis it may be said that the strata in the district north of the Chestnut Hill fault show no definite evidence of inversion. On the contrary, the ripple-marked sandstones in Brighton and the apparent conformable passage of the conglomerate upward into slate tend to show that the strata are in their normal attitude, though it may be said that an unconformable contact might be concealed by the drift north of the conglomerate boundary. In the second hypothesis the evidence of faulting now at hand seems to favor the downthrow rather than the upthrow of the slates, for in both the northern escarpment of the crystallines and the conglomerate escarpment along the railroad at West Newton the dip of the supposed fault planes, so far as it can be determined, is toward the slate, making the latter appear as a down-faulted block. The Auburndale ledges lie just about on the strike of the supposed fault at West Newton, or perhaps a little to the north of it, so that the apparent drag indicated

by the steep southerly dip of the strata at that locality may be due to the fact that the beds in question lie on the north or downthrow side of the fault.

On the supposition of the Carboniferous age of the slate the apparent conformable succession of the strata and the occurrence of the conglomerate at Medford are readily explained. The supposed downfaulting of the slates offers no difficulty, since in that case the effect would be simply to bring higher beds of the series in opposition to lower beds. The evidence in favor of either Cambrian or Carboniferous age cannot be said to be conclusive, but the latter hypothesis accords better with the structural data now at hand, and has therefore been represented in the accompanying section (Plate 6).

——:—*The Brighton-Newton Area.* According to Crosby the Brighton Newton area forms an anticline relatively symmetrical at the western end where the melaphyr extending eastward forms the axis. Toward the east the anticline is broken down and becomes a faulted monocline. The southward thrust of the conglomerate arch has crushed and partly concealed the narrow syncline of slate along the southern border. According to H. G. Woodward no less than six beds of melaphyr, ranging in thickness from 25 to 200 feet, and one important tuff bed, besides several dikes of melaphyr, are included in the area (Crosby, g, p. 12).

Burr, on the other hand, finds no evidence of anticlinal structure in this area. The conglomerates south of the melaphyr dip northward at prevailingly low angles, while north of the melaphyr the dips are still in the same direction, at somewhat steeper angles. Thus the whole forms a monocline of increasing steepness towards the north. Furthermore, he finds no repetition such as might be expected in the case of anticlinal structure. The conglomerates, with interbedded sandstones and slates, grow progressively finer northward and there is no swinging of strikes at the eastern end of the conglomerate such as might be expected were the strata arched (Burr, b, p. 64–65). The writer's observations have not been extended throughout this entire field but in traverses both north and south of the melaphyr region from Brighton to Newton Upper Falls he has found the dip of the conglomerate prevailingly northward and the strike fairly uniform, with local variations only, in a northeast-southwest or nearly east-west direction.

South of the monoclinal area occurs a narrow slate belt which is exposed in several localities near the eastern part of the Chestnut Hill Reservoir, on the north side of Beacon Street at Newton Center and

westward near the Charles River. Crosby interprets the structure as a syncline closely folded and wedging out westward. Towards the east he believes that the syncline broadens as it approaches Boston Harbor. He recognizes the thrust faulting at Chestnut Hill Reservoir and at Newton Center but considers these dislocations merely as interruptions of the syncline. (Crosby, g, p. 11). Burr, on the other hand, considers the faulting as the main feature, though he recognizes the possibility of synclinal tendencies at Chestnut Hill (Burr, b, p. 63). He states emphatically that there is no swinging of strikes at the west end of the slate belt to indicate synclinal structure (ibid., p. 65). He believes that the fault dies out westward, for at Newton Lower Falls fine conglomerate such as usually occurs immediately beneath the slate appears, as if the throw had not been sufficient to bring up the lower members of the conglomerate. Eastward, too, he thinks the fault dies out, for the conglomerate ridges disappear in that direction (ibid., p. 63–64). The latter supposition does not, however, necessarily hold, since a general eastward pitch of the axes of the conglomerate would carry the latter below the slate in that direction. With slate on both sides of the fault the determination of the latter would be difficult.

——:—*The Savin Hill-Brookline Conglomerate.* A broad conglomerate area extends from Savin Hill through the northern part of Dorchester, Roxbury, West Roxbury, Brookline, and Newton to the Charles River. On the north it dips beneath the narrow slate belt just described and on the south it also passes below the slate, with which it appears to be entirely conformable. The northerly dips are relatively gentle, usually not exceeding 20°–30°, but the southerly dips are steeper, amounting to 60° or 70°. Thus the conglomerate in this zone forms a broad and flat-topped anticline, somewhat unsymmetrical, with the steeper dip toward the south (Crosby, g, p. 9–10; Burr and Burke, p. 183). The conglomerate in this area is abundantly exposed and the stratigraphic relations are fairly clear. On account of the decrease in size of the pebbles from Brookline to Savin Hill it is believed by Crosby (b, p. 234–235) that the latter beds represent higher members of the series and that therefore the axis of the anticline pitches eastward. The general disappearance of the conglomerate beneath the slate in that direction leads to the same conclusion. It may be remarked, however, as noted by Crosby (loc. cit.), that diminution in size of pebbles does not necessarily imply a higher horizon, since it has been shown that this feature of a conglomerate may mean simply a greater distance from the source of supply.

——:—*The Dorchester-Roslindale Slate.* A relatively narrow belt of slate extends from Roslindale nearly due east through Franklin Field and Dorchester to the coast. Outcrops are few. Topographically the belt is marked by a broad valley which is especially well defined near Roslindale and is utilized by the Dedham Branch of the New York, New Haven and Hartford Railroad. The structure of this belt has long been regarded by Crosby as a closely folded, somewhat unsymmetrical syncline, because the conglomerate both north and south seems to dip beneath it (Crosby, g, p. 9). There has been, however, some difference of opinion with regard to the matter. Dodge, for example, stated in 1881 that he did not know of a single fact supporting the supposition that the West Roxbury-Dorchester slate lies in a syncline (Dodge, b, p. 209). Nevertheless the writer is inclined to accept Crosby's view of the structure, for at the corner of Bellevue Avenue and West Street in Roslindale a beautifully glaciated ledge of slate that has been rather recently uncovered shows what appears to be a faulted synclinal fold. The rock at this place is rather sandy and in places well banded. The entire length of the exposure from north to south is about thirty-five or forty feet. Variations in texture occur along this line. For the first twenty feet from the north the rock is sandy, then follow five or six feet of alternate sandy and slaty layers, with some development of cross-bedding, and finally ten feet of sandy slate. The northern limb of the fold strikes N 67° E and has a dip of 50° south. As the fault is approached the strike becomes a little more easterly and the dip somewhat steeper. The fault is marked by a brecciated zone three to six inches wide which strikes N 57° E and has a vertical or steep southerly dip. The southern limb of the fold is parallel in strike and dip to the fault zone. The strata of the two limbs do not correspond and the evidence of inversion of the layers of the southern limb is not particularly clear. It is possible that the slate belt may be merely a slaty member of the conglomerate series which has been interrupted by a strike fault, and that the appearance of folding may be illusory. But this would involve a greater thickness and a somewhat different arrangement of strata on the south side of the great Savin Hill-Brookline anticline than appears on the north side. Moreover, the conglomerate to the south of the slate belt grows coarser in the vicinity of Mattapan and Hyde Park in much the same way that the similar change occurs northward toward Brookline. Thus the suggestion is strong that the strata south of the slate belt appear in descending order in the same way that they do northward, that the slates occupy a strati-

graphically higher position than the conglomerates on either side, and that they are caught in a pinched and faulted syncline that is slightly overturned northward. This interpretation has been represented on the accompanying section (Plate 6).

——: — *The Hyde Park-Mattapan-Squantum Area.* From Hyde Park east-northeast to Squantum there is a zone of conglomerate with occasional included sandy and slaty zones and masses of basic lava. The dips are prevailingly southerly at relatively high angles, 60°–70°, or even higher. Toward the southwest the area is split by a mass of felsite with irregular boundaries that projects northeastward from Dedham and Hyde Park. Crosby believes the general structure of this zone to be anticlinal with the western part eroded and the limbs separated by the underlying granite and felsite (g, p. 7). The flow structure of the felsite originally horizontal is now everywhere highly inclined and chiefly vertical, showing that the plication of the Carboniferous sediments was shared by their volcanic floor (Crosby, p, p. 80). According to his view the great arch is not a simple fold, however, for it is complicated by several sharp synclines and is broken by numerous important faults. The slate is preserved only in narrow belts wedged between larger masses of conglomerate by the minor folds and faults. He believes also that there are at least three beds of melaphyr and one important bed of porphyrite interstratified with the series (g, p. 7). Later studies by the same writer and Miss Bascom have shown that some of the lavas formerly classed as melaphyr are really less basic than that type (Crosby, p, p. 40). The anticline narrows eastward and the axis pitches east (ibid., p. 36).

The present writer has not studied this complicated region with sufficient care to enable him to verify or disprove Crosby's view of the details of structure but the general view of the region as an anticline seems to be warranted by the structure of the slate belt immediately to the north and by the direction of variation in texture, as already noted. The prevailing southerly direction of the dip shows that the strata have been almost isoclined and slightly overturned toward the north, as indicated on the accompanying generalized section (Plate 6). The felsite area is there represented as involved in the anticlinal structure, in accordance with Crosby's view above noted. As regards the complications of the anticline it may be said that the statement about the preservation of the slate above quoted seems a little sweeping, for in a description of the series at Milton Lower Mills Crosby speaks of numerous alternations of conglomerate, sandstone, and slate (g, p. 8). That minor folding and faulting

do occur, however, is shown by the anticline of slate in the railroad cut just south of the Neponset River at Milton.

At Squantum the structure seems to be a prolongation of that just noted in the southwestern part of the belt. The dips are all southerly and more or less steep but the general structure seems to be anticlinal. The main characteristics of the structure at Squantum are thus outlined by Crosby (ibid., p. 8): (1) the cleavage across the bedding of the slate; (2) the coarseness and irregularity of the conglomerate; (3) the repeated alternations of thin layers of sandstone and brownish slate; (4) faults on a large and small scale; (5) closed and overturned folds.

——:—*The Neponset-Hough's Neck Region.* Between the Hyde Park Squantum anticline and the crystallines to the south there is a belt of slate that is relatively narrow in the west but broadens rapidly eastward. The general structure, according to Crosby (p, p. 35), is synclinal, but outcrops are few. In the western part of the area, near the granite, the slate is underlaid by arkose, which is somewhat kaolinized but is nevertheless quite granitic in appearance and the whole shows a northerly dip varying from 40° to 70° (n, p. 479). Eastward along the granite boundary the arkose and overlying slate give way to conglomerate (ibid., p. 482) which, northwest of President's Hill, grades northward through various alternations into the main body of dark gray slate, with northerly dips of 85° to 90° (ibid., p. 484). The southerly dips of the conglomerate series of the Hyde Park-Squantum anticline on the north and the northerly dips of the slates along the granitic border on the south form the basis for the idea of synclinal structure. The dips along the southern border appear to be somewhat steeper than those along the northern boundary so that in the western part of the area at least the syncline seems to be slightly overturned northward and has been so represented in the accompanying section (Plate 6).

Eastward in the general direction of the strike of the conglomerate near President's Hill occurs the conglomerate at Rock Island, Hough's Neck, with its associated slate and melaphyr. The interpretation of the structure of this area depends largely upon the view held regarding the nature of the melaphyr mass. The latter has been the subject of some controversy, and has been considered both as a dike and as a flow. The melaphyr forms a ridge flanked on either side by conglomerate passing into slate. On the south side this passage may actually be seen, but on the north side it does not appear, though its presence is inferred from the occurrence of low outcrops of slate on the

same strike a mile or more to the west and from the prevalence of slate drift along the beaches to the north. Professor Wolff, in a petrographic study of the melaphyr, describes the latter as a dike (p. 231). Professor Crosby, on the other hand, from the unsymmetrical section presented by the melaphyr and from differences in the character of the conglomerate on the north and south of the melaphyr, believes the latter to be a flow (n, p. 494), which, together with the inclosing sediments, is now inclined southward and forms part of the southern limb of a faulted anticline that extends westward to the granite border and connects westward with the conglomerate already noted near President's Hill (ibid., p. 498). On account of the absence of conglomerate outcrops between Rock Island and the granite boundary, and the somewhat doubtful character of the conglomerate near President's Hill, the conglomerate area has not been extended in that direction on the map (Plate 7).

South of the supposed Hough's Neck anticline slate again appears which is apparently similar to that immediately north, with which it seems to merge eastward and also westward, though in the latter direction it may be interrupted by the supposed anticline. The age and stratigraphic position of this whole area of slate south of the Hyde Park-Squantum anticline is somewhat doubtful. If the slates are Carboniferous they are doubtless conformable with the conglomerates and overlie them. So far as the evidence of superposition of strata may be observed in the field it is favorable to this view.

These slates, however, bear a close lithological resemblance to those of the Somerville area and the same obscure, possibly organic, impressions observed in the Somerville slates are found in the slates near the Norfolk Downs station at Wollaston (Woodworth, a, p. 126). If the Somerville slates are considered as Cambrian it would seem that the Neponset slates should also be so considered. Evidence in favor of this view is not entirely wanting. Around the eastern end of the Blue Hill Range the lowland is continuous from the region of the Neponset slate to the localities at Weymouth and Braintree, where known Cambrian fossils have been found. Slate patches or outliers, cut by granite dikelets, rest on the granite at Quincy (Crosby, n, p. 428 et seq.). Areas of slate near the Boston and Hyde Park boundary in the eastern part of the Stony Brook Reservation and the immediately contiguous territory show igneous contacts with fine granite and quartz porphyry, irregular dikes or apophyses of quartz porphyry and more regular dikes of normal felsite (Crosby, p, p. 41–42). These igneous rocks are known to be Post-middle Cambrian because of their relations

to the slates of Braintree, and they are believed to be Precarboniferous because they are represented by pebbles in the conglomerate which is supposably of Carboniferous age.

The relations of the slates at Hyde Park to the conglomerate series are not clear. The small slate areas at Quincy seem to be merely inclusions or outliers. The sandstone or quartzite at Green Lodge, referred to on page 98, resembles to some extent the quartzite at Somerville and Everett, but its stratigraphic relations are not known. The area is so covered with drift and alluvium that boundaries are merely conjectural.

On the supposition that the Neponset slate is Carboniferous these Precarboniferous areas must be regarded as outliers or inliers of Cambrian sediments resting on the underlying granitic rocks. There still remains the difficulty of fixing the relations between the Neponset slate on the north and the Weymouth and Braintree slates on the south. Crosby has met this difficulty by assuming a fault along the northern boundary of the granitic area, extending eastward somewhere beneath the drift between Hough's Neck and the Lower Cambrian beds at Mill Cove and East Quincy (n, p. 508). The supposition that the slates are Cambrian involves even greater difficulties, for the field evidence, so far as it may be obtained, appears to favor conformable passage upward from conglomerate to slate. If the latter is really Cambrian its presence apparently above the conglomerate must indicate an inversion of the strata, or perhaps an overthrust fault, the whole complicated by minor folds or faults to account for such features as the Hough's Neck Conglomerate. It must be admitted that there is no evidence in favor of such conditions. On the contrary, the occurrence of southward dipping, ripple-marked sandstones in normal position in ledges by the Neponset River (Boston VI, Y 26) is opposed to the idea of inversion of the strata but is favorable to the supposition of anticlinal structure.

——:—*The Southern Boundary.* The southern boundary of the Boston Basin sediments is believed by Crosby to be a fault of perhaps 2,500 feet displacement, with the downthrow on the north (n, p. 509). The facts upon which this view is based are the following: the cutting out of a great body of Cambrian slate, the brecciation of the granite, the rapid narrowing of the conglomerate and the exceptional induration of the latter as if by hydrothermal action (ibid., p. 428). The conglomerate here mentioned is the western extension of the supposed anticline, of which the conglomerate and the associated rocks at Rock Island, Hough's Neck, form the southern limb. This anticline is believed to be cut diagonally by the boundary fault (ibid., p. 498).

West of the conglomerate, arkose occurs along the southern border. No special significance appears to be attached to the arkose by Crosby other than that it shows that the granitic rocks of the Blue Hills area were subject to erosion during the accumulation of the sediments (ibid., p. 479). He regards the arkose, together with the overlying slate, as upper members of the Carboniferous series. It may be remarked, however, that arkose in other parts of the Boston Basin and in the Norfolk and Narragansett Basins is more associated with the basal beds of the series. At Pondville, in the Norfolk Basin, for example, the arkose rests upon the granitite and is overlaid by shales, conglomerates and sandstones. The formation of arkose requires certain climatic conditions that will be discussed later. These conditions would doubtless obtain not only over the combined areas of the several basins under consideration but probably also over far wider regions, so that deposits of arkose in the several basins might be regarded as in a measure synchronous. Since the arkose is usually associated with the basal sediments of the southern basins it is probable that the same is true of the Boston Basin also, and that the arkose along the southern border really represents the basal member of the series. This supposition is opposed to the view that a fault passes between the granite and the arkose. More probably it passes to the north through the slate somewhere beneath the drift. East of the conglomerate the evidence is uncertain. So far as can be judged the rock is all slate under a deep drift cover. Crosby believes that the northern part of this area is referable to the Carboniferous series and the southern part to the Cambrian. He therefore produces his fault almost due east from the northern side of President's Hill to the coast, in order to obtain the desired separation. In the accompanying section (Plate 6) the fault has been indicated along the granitic border in accordance with Crosby's idea, but on account of the probably basal character of the arkose the writer has more recently formed the opinion that it should be placed north of the arkose at least, and perhaps north of some of the slate also.

——:—*Outlying Areas:—Wellesley-South Natick.* From the vicinity of Newton Lower Falls southwestward through South Natick, scattering outcrops of conglomerate, slate, and melaphyr indicate that the Carboniferous rocks of the Boston Basin are extended in that direction. The most remote outcrop is southeast of Farm Pond in Sherborn, reported by Tilton. The area is largely drift covered. Many of the ledges have been intensely metamorphosed and recognition of their true character is uncertain. The general structure of the

region is believed by Crosby to be a broken syncline (g, p. 13). The dips are steep northwesterly and almost isoclinal. The highly arkosic and felsitic character of the rock in the vicinity of granitic and felsitic areas indicates that the rocks in this region probably represent the basal portions of the series. The high dips and the highly metamorphosed condition of the rocks show the intensity of the folding to which the latter have been subjected.

——:——:—*Hingham.* The structure and stratigraphy of the Hingham rocks have been worked out in great detail by Crosby in one of his later papers on the Boston Basin. According to his interpretation an anticlinal axis, occupied by granite, extends in a nearly east-west direction north of the railroad and of Beal Street. At the western extremity of the axis melaphyr and sediments curve around the granite and dip away from it, forming the nose of an anticline. Eastward, in the vicinity of Hockley Lane, a transverse fault separates this area from one in which the order of succession is inverted and melaphyr appears on the south side overlying the conglomerate. Probably the sediments in this belt are separated from the granite both north and south by important faults, bounded northeast by the great fault along the east side of Hingham Harbor. Northwest from the west end of the granitic axis a steep narrow broken monocline separates the granite from the trough holding the great mass of the slate. The faulted monocline contains a second band of melaphyr, which broadens northeast, forming the large quadrangular area east of Huit's Cove. This area is bounded on all sides by downthrow faults. On the west the upper conglomerate and slate dip away from the melaphyr. On the north the downthrow of the sediments conceals the conglomerate and the slate lies against the melaphyr. On the south the narrow monocline separating the body of the melaphyr from the granite broadens until it reaches the fault at the northwest end of Squirrel Hill, where it changes, perhaps abruptly, to a broad and shallow syncline separated by a strike fault from the southerly monocline of conglomerate and sandstone on the north. These features probably extend east under Broad Cove and Otis Hill. The monocline is clearly seen at Melville Garden and in the islands of the harbor. Westward from the Garden the east-west strike and southerly dip change steadily but rapidly to a north-south strike and a westerly dip. Folds are the dominant structure of the Hingham area, but they are greatly modified by faults (Crosby, l, p. 200–202).

The following table gives the Hingham section as determined by Crosby (ibid., p. 203):—

Granite Rocks (diorite, granite, felsite).

1.	conglomerate (basal) — thickness uncertain	
2.	melaphyr	120–240 feet
3.	fine conglomerate and sandstone alternating .	120–200 "
4.	gray slate	40– 60 "
5.	conglomerate, sandstone and slate alternating	100–170 "
6.	gray and red slate	90–130 "
7.	conglomerate	30– 50 "
8.	red slate	20– 40 "
9.	conglomerate	40– 50 "
10.	red slate	20– 30 "
11.	conglomerate	75–100 "
12.	red slate	50– 75 "
13.	sandstone and conglomerate alternating . .	200–300 "
		905–1445 feet
14.	gray slate	500 +

Melaphyr occurs in only one horizon at Hingham, near the base. The distribution of the scoriae and amygdules of the melaphyr are such as to suggest a composite flow (ibid., p. 212).

——:——:—*Nantasket.* An isolated area of sediments with interbedded lavas and tuffs occurs at Nantasket. The whole has been greatly broken by faults and cut by dikes. Crosby's account of this region, published in 1894, is the most complete and detailed study at present available, and the following brief summary is taken largely from his work. According to his interpretations the entire peninsula of Hull, with the exception of a narrow belt passing under Strawberry Hill is underlaid by slate, but the entire peninsula is composed of drumlins and connecting beaches of sand and shingle, and there is only one outcrop of slate — a single ledge on the south side of Thornbush Hill (Crosby, k, p. 1) — so that the interpretation is based on scanty evidence. Beneath Strawberry Hill he thinks the underlying rock is conglomerate, though no outcrops appear, for at Harding's Ledge, off shore in the line of strike of Bumpkin Island and Strawberry Hill, indications of conglomerate have been found, and it is supposed that the conglomerate of Hough's Neck may be continued in that direction (ibid., p. 104).

The mainland immediately adjoining the southern end of the penin-

sula is composed almost entirely of rugged ledges of conglomerate and melaphyr that form a striking contrast to the smooth and gentle outlines of the drumlin and beach formations. Crosby considers the whole area a monocline, which, though shattered by numerous faults and dikes, exhibit low and uniform dips. Along the north margin of Atlantic Hill at Rocky Neck the dip is south-southeast 10°–20°. Southward it diminishes and becomes more easterly. The sedimentary rocks with their included beds and granitic floor are broken by longitudinal and transverse faults into blocks extremely variable in size and form. The principal longitudinal faults such as the border of the granite from Straits Pond to Weir River Bay have the downthrow to the north. The displacement is so great that although the rocks dip toward the granite, one passes from older to newer rocks in going northward. The conglomerate is so homogeneous and the tuff so local that one must depend largely on the lithological characteristics of the interbedded lavas in correlating adjacent ledges as well as the more remote (Crosby, k, p. 23). The Nantasket section shows the granitic floor overlain by six beds of conglomerate alternating with five sheets of melaphyr and tuff, with one sheet of porphyrite, the whole aggregating 600 to 960 feet in thickness (ibid., p. 24). The tuff beds are local. The lava flows are clearly composite, in some cases representing several eruptions in quick succession. This is conspicuously true of the great sheet forming Atlantic and Center Hills. The faults are either approximately east-west or north-south and the dikes are grouped in three systems: (1) the oldest, N 75–80 E; (2) S 75–80 E; (3) the newest, N S (ibid., pp. 25–26).

——:——:—*The Harbor Islands.* Lovell's, Gallup's, George's, and Great Brewster Islands are drift covered. The others, almost driftless, form part of a great synclinal fold of slate, with intrusive diabase; Calf Island is on the north side of the synclinal and the Brewsters are on the south side (Crosby, g, p. 1).

——:—*Thickness:* The only place in the Boston Basin where anything like a complete section has been measured is at Hingham. Crosby regards the strata there from lowest conglomerate to highest slate as one series. The maximum thickness as given in the above table is 1,445 feet, but neither the thickness of the basal conglomerate nor of the upper slate is known. According to Crosby's view the maximum thickness is certainly 2,000 feet and if the Nantasket beds are included it is probably as much as 3,000 feet (l, p. 266). If the Somerville slates are considered as Carboniferous and as upper members of the series, then the maximum thickness already noted for that

formation, 2,300 feet, may be added to the figures here given, and a maximum thickness of about 5,300 feet may be obtained for the sediments of the Boston Basin.

——:—*Summary of Structure.* The foregoing discussion of the structure may be summarized as follows:—

(1) The escarpment forming the northern boundary of the slates is suggestive of a fault. No valid arguments have been brought against this supposition.

(2) The age relations of the Somerville slates are indeterminate, but the supposition of Carboniferous age accords best with the known structural facts.

(3) The area from Brighton south to Chestnut Hill Reservoir and west to Newton Upper Falls is probably a monocline of increasing dip toward the north. The Chestnut Hill slate belt marks the line of a great overthrust fault with the fault plane dipping gently north.

(4) The Savin Hill-Brookline conglomerate area forms a broad, flat-topped, unsymmetrical anticline.

(5) The Dorchester-Roslindale slate belt forms a narrow, faulted syncline.

(6) The Hyde Park-Mattapan-Squantum conglomerate zone forms a broken and faulted anticline, overturned slightly northward and eroded at the western end deeply enough to separate the limbs.

(7) In the Neponset-Hough's Neck region the question of age again arises in connection with the slate. The structural evidence favors the supposition of Carboniferous age. Hough's Neck may represent part of a faulted anticline.

(8) The presence of arkose, which elsewhere forms a basal member of the series, is opposed to the supposition of a fault along the granitic border, as postulated by Crosby. If the arkose is really basal and the Neponset slate is Carboniferous, then the fault probably occurs under the drift north of the arkose and granite and the latter are brought up to the stratigraphic level of the younger sediments.

(9) The outlying Wellesley-South Natick area is probably a broken syncline. The arkosic nature of much of the sediments indicates that probably the basal members of the series are exposed.

(10) The Hingham area affords the only section that has been measured. The maximum figure, 1,445 feet, does not include the base of the conglomerate nor any of the overlying slate. The structure is characterized by folds greatly modified by faults.

(11) Nantasket is a faulted monoclinal region, with several interstratified flows of lava and beds of tuff.

(12) The Harbor Islands are composed of slate and appear to form parts of a great syncline.

(13) The thickness of the conglomerate series, together with the overlying slates, probably amounts to as much as 5,300 feet.

(14) The disposition of the conglomerate and slate areas on the map (Plate 7) shows that the arms of slate widen and the conglomerate masses grow narrow toward the east, indicating a general structure of anticlinal and synclinal folds pitching east, so that in the western part of the area the lower members of the series are exposed, while in the eastern part the highest beds appear.

Relations to the Melaphyrs. In several rather widely scattered areas of the Boston Basin melaphyr accompanies the conglomerate series. The main localities are at Nantasket, Hingham, Hough's Neck, Brighton, Brookline, and the Newtons. It has already been noted (page 202) that rocks in the Neponset valley assigned to the melaphyrs have been shown to be less basic than that type. At Nantasket and Hingham the lavas are generally believed to be flows interbedded with the conglomerate series. At the former locality no less than five beds of melaphyr and tuff and one of porphyrite have been made out by Crosby, as indicated in a previous paragraph. The occurrence of the tuff, though limited, is excellent evidence of the effusive character of the rock and this is supplemented by the occurrence of numerous pebbles of the basic lavas in the conglomerates that overlie the melaphyrs.

At Hingham the melaphyr mass is believed to represent a composite of several flows, on account of the distribution of the scoriaceous and amygdaloidal matter. According to Crosby the contact of the melaphyr with the arenaceous conglomerate is parallel with the strike of the conglomerate, with only minute irregularities. The melaphyr does not penetrate the conglomerate more than the latter does the former. Irregular cracks in the lava are filled with fine sand now highly ferruginous. There are no distinct inclusions of the sediments in the melaphyr but a few small pebbles of the melaphyr occur in the conglomerate near the contact. The conglomerate and sandstone exhibit no special alteration or induration. It is evident that the sedimentary rocks were deposited on the melaphyr for they fill cracks in it and are partly made up of debris from it. Near the contact the melaphyr fragments are large and angular but the conglomerate as a whole is composed chiefly of felsite and granite (Crosby, 1, p. 212–214).

The relations of the melaphyr to the conglomerate at Hough's Neck

have been the subject of some diversity of opinion. Professor Wolff has described the melaphyr as a great dike. He states that at the west end of the outcrop, on the south side, the junction of the melaphyr with the conglomerate and red sandstone is very irregular; large and small tongues of the dike penetrate into the conglomerate, the latter rock striking N 60°–80° W and dipping 70° S. The junction between the two rocks, he says, is sharp and well marked and the dike seems often amygdaloidal near the contact. Sections of the latter show that the dike is composed of a mass of small feldspars, showing a beautiful fluidal arrangement, while they are often bent when in contact with the line of the conglomerate. On the north side there is a fine vertical exposure where the rock is seen to stand almost vertically, the dike cutting the slate and conglomerate a little irregularly but nearly parallel with the strike (Wolff, p. 231–232). Professor Crosby, on the other hand, advocates the idea that the melaphyr is a flow. He maintains that the amygdaloidal and scoriaceous character of the upper part of the rock and the unsymmetrical section of the melaphyr are normal for a flow but abnormal for a dike. The highly but minutely irregular form of the upper contact, the compact and fluidal texture of the melaphyr near the contact and the abundance of the debris of the melaphyr in the base of the overlying conglomerate, while such debris is lacking in the underlying conglomerate are adduced as further evidence of the effusive nature of the rock (Crosby, n, p. 494). The greater irregularity of the south contact of the melaphyr is noted by both Wolff and Crosby. Since the rock on both sides of the melaphyr is conglomerate of much the same character, it would seem, if the melaphyr were a dike, that both north and south contacts would have approximately the same degree of irregularity; yet there is a distinct difference in this respect. The amygdaloidal character of the melaphyr near the southern contact is noticed by both observers. While no general law can be stated, it may be said that such a characteristic is unusual for a dike but may well be expected in the case of a flow. The fluidal arrangement of the feldspars and the bending of the latter near the contact are both characteristics suitable for a dike, yet flow structure is often a well-marked feature of effusive rocks and it might well be that feldspars caught in the zone between the slower moving surface of the gradually congealing rock and the more rapidly moving interior would become bent or distorted. The occurrence of melaphyr debris in the conglomerate on the south, and the absence of such components in the conglomerate on the north are strong points in favor of the effusive

theory. Nevertheless, at certain places on the south side of the melaphyr the suggestion of intrusive contact is strong. Little tongues of melaphyr appear to cut across the bedding of the slaty layers and to mingle with the matrix of the conglomerate so as to enfold the pebbles. Perhaps the first feature may be accounted for by the deposition of slaty material in the minute crevices of the rough surface of the lava, while the second may be the result of the infiltration of fine mud, derived from the erosion of the surface of the melaphyr, into

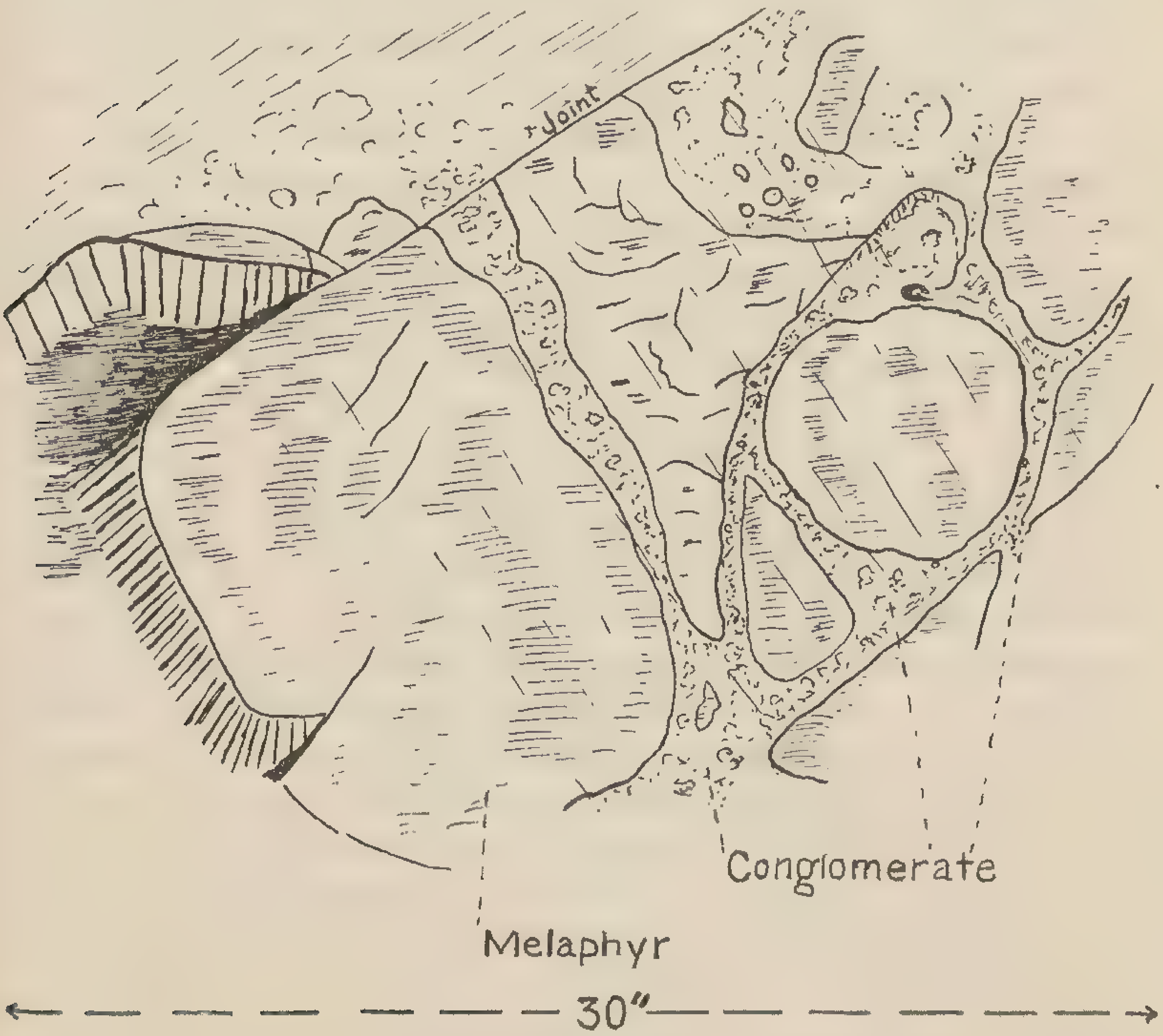

FIG. 6.— Conglomerate and melaphyr at Hough's Neck.

the matrix of the conglomerate. Perhaps, too, after the surface of the flow had cooled, cracks in the crust thus formed permitted the extrusion of the still molten lava below into the rapidly accumulating, unconsolidated sediments above. It must be admitted, however, that this latter supposition is hardly tenable since the only evidence of such cracks in the melaphyr is found in the numerous dikes that occur in it, and these latter, with one or two exceptions, do not cut

the conglomerate. The weight of the evidence seems to the writer to favor the idea that the melaphyr is effusive. Figure 6 represents a portion of the contact along the south side of the exposure.

The Brighton, Brookline, and Newton areas have been included in a discussion centering on the question of effusive or intrusive origin. The main participants in the most recent phases of the controversy have been Crosby and Burr, the former upholding the effusive theory and the latter the intrusive. The main arguments cited by Burr in defense of the intrusive theory are: (1) wherever contacts between the igneous rocks and the sediments occur the latter are penetrated by tongues of melaphyr which cut across the bedding and display little sympathy with the stratification; (2) there is always a baked, discolored, and indurated contact zone in the sediments; (3) no pebbles, definitely determinable as melaphyr, occur in the conglomerates that appear to overlie the melaphyr; (4) the melaphyr occurs at varying horizons and in connection with both anticlinal and synclinal structures,—a feature quite in accord with the intrusive idea (Burr, b, p. 54–61). Crosby maintains on the other hand: (1) that dikes of such width (3,000 feet), without holocrystalline structure but with well-marked amygdules, cannot be regarded as probable; (2) that in the area between Newton Upper Falls and Newton Highlands several bands of melaphyr appear interbedded with the conglomerate and that these bands are solid, homogeneous, and holocrystalline toward their southern borders but more slaty, amygdaloidal, and scoriaceous northward; (3) that these bands are covered with conglomerate which is crowded near the contact with angular fragments like the melaphyr, but becomes practically free from melaphyr masses within two yards of the contact; (4) that the melaphyrs of Boston are essentially unlike known dikes or sills; (5) that the irregular contacts may be explained as sedimentary contacts with the lava surface; (6) that the supposed baking is the result of silicification from the chloritization of the melaphyr; (7) that the reddening is caused by the impregnation of the sediments by the ferruginous materials of the melaphyr (Crosby, o, p. 324–326). Modifying to some extent his former views, Crosby supports Burr's contention that the melaphyrs are not confined to one horizon (ibid., p. 326).

The writer has visited many of the localities described by Burr and has also had the opportunity of examining his specimens and slides. As regards the Brighton area he is in full accord with Burr's conclusions. The mere fact that it is unusual for heavy bodies of intrusive rock to lack holocrystalline structure and to possess amygdaloidal

characteristics does not in itself constitute a valid argument against the possible occurrence of such rocks. It may very well be conceived that large masses of lava have risen through sedimentary rocks near to the surface without actually breaking through, or that such masses may even have broken through the surface at some stratigraphically higher level, so that both the higher sediments and the outpoured lavas were eroded away. In either case the lava close to the surface would partake largely of the character of rocks that were actually effusive. In the case of the Brighton rocks it does not seem to the writer that the irregularities of contact can be explained as the result of sedimentation on the irregular surface of the lava; for in specimens of sandstone and melaphyr contacts, examined on the polished surface with a microscope, the layers of sandstone appeared bent and broken as the contact was approached, and in the immediate vicinity of the latter the layers became fused to a homogeneous, silicified mass, highly ferruginous, in which the layer structure could no longer be distinguished. Even supposing the silicification and discoloration to be due to the causes suggested by Crosby it would seem hardly possible that the layers would be bent and broken at the contact, were the latter sedimentary. Some of the larger features of the contact are shown in Plate 4, which gives views of the east and south sides of the ledge a few hundred yards northeast of the sharp bend in Commonwealth Avenue (Boston V, I 28). On the eastern side (A) the irregular vertical contact is seen cutting across the bedding of the sandstone. On the south (B) an irregular strip of sandstone appears included in the melaphyr. Figure 7 (A) represents more minute features observed in a ledge back of the convent (Boston V, G H 27).

In the region of Brookline and Newton the evidence of intrusive contact is equally clear in many localities. The same characteristics of irregular igneous contact with the baked and discolored zone are to be seen at a number of localities, notably at a large flat ledge a few rods southeast of the city quarry at Thompsonville. There melaphyr and sandstone are exposed in the intimate relation shown in Figure 7 (B). Evidence of the intrusive nature of the melaphyr is often obtained at some distance from the actual exposures of that rock. For example, on the south side of Walnut Hill, at several points among the fine conglomerate exposures in that vicinity, the matrix of the conglomerate is impregnated with a dark red igneous rock which envelops the pebbles and mingles with the finer fragments. It is usually local and irregular in occurrence and has often become schistose with the shearing of the rock. Similar impregnations have been

noted on the south side of Newton Street in Brookline, a quarter of a mile east of the north end of South Street, in ledges near the west side of South Street a mile from the same point, and at the Arnold

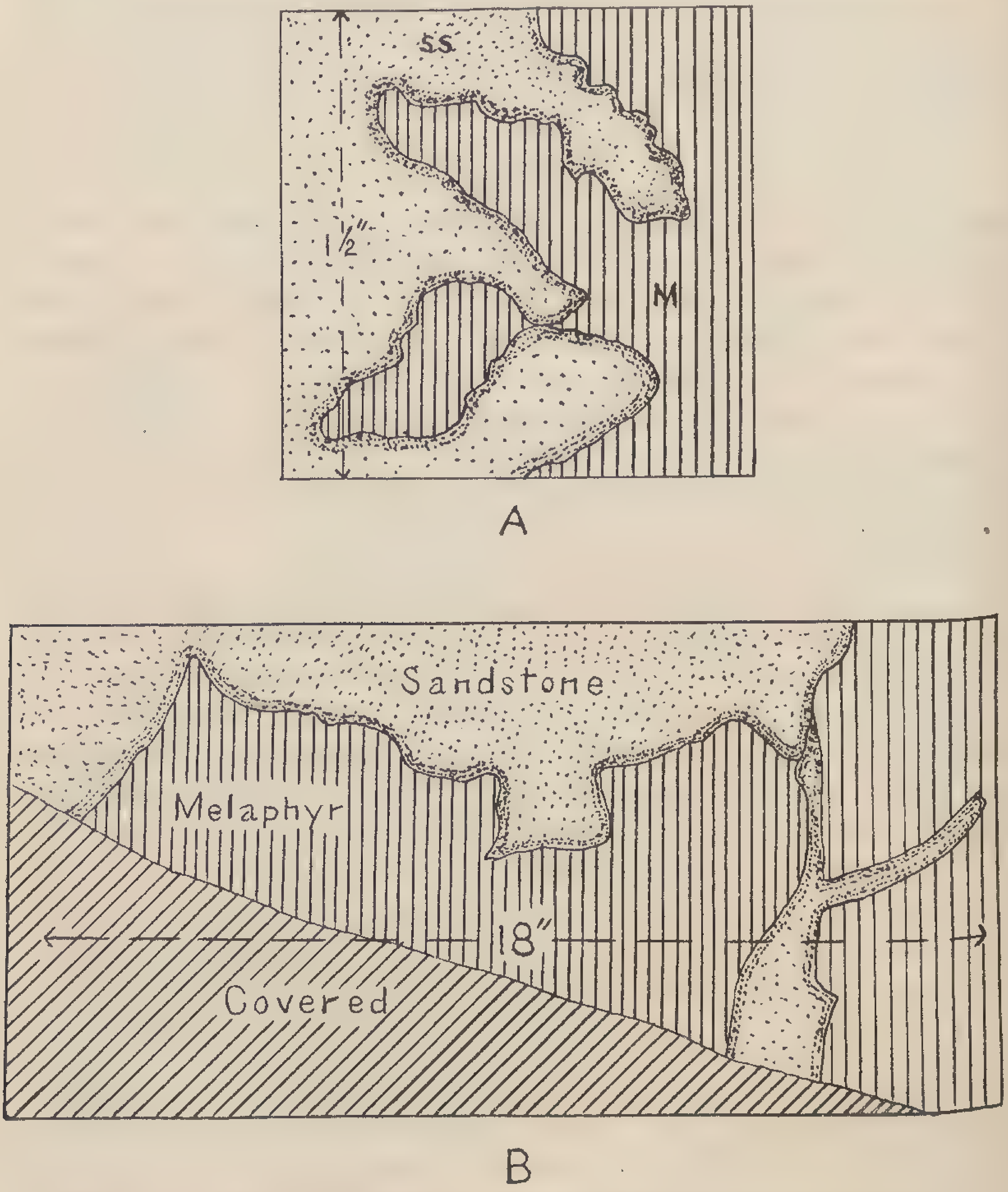

Fig. 7.— A. Contact of melaphyr (M) and sandstone (ss) in the ledge back of the convent at Brighton (Plan).
B. Contact of melaphyr and sandstone just southeast of the city quarries at Thompsonville (Plan).

Arboretum two miles southeast of Walnut Hill. That the impregnations are truly igneous and not mere infiltrations of fine mud is shown

by their tongue-like appearance on the polished surface and by the fact that in thin sections under the microscope they appear as irregular tongues of ferruginous glass, sometimes devitrified, with a well-developed flow structure. It may perhaps be questioned whether these igneous intrusions are sufficiently basic to warrant their being classed with the melaphyrs, but since the latter are the only contemporaneous lavas yet recognized in this region, and since some of the impregnated rocks are near masses of melaphyr and their igneous constituents resemble some of the facies of that rock, it seems safe to conclude that the impregnations belong to the same series.

On the other hand it is not equally certain that none of the lava in that section is effusive. As regards Crosby's contention that the upper and lower parts of the melaphyr bands show differences in texture, the writer is not prepared to offer an opinion, since he has not carefully examined the localities noted; but with reference to the question of melaphyr pebbles in the conglomerate he can say that on the east side of Langley Street in Newton Center, three-quarters of a mile southeast of the railroad crossing, he found in a conglomerate ledge by the roadside a basic pebble that in thin section under the microscope appeared to be melaphyr. Thus the contention of Burr that none such occur seems a little sweeping. Probably the truth of the matter is that in this region both the intrusive and effusive types of melaphyr occur.

——:—*Summary of Relations to the Melaphyrs.* At Nantasket, Hingham, and Hough's Neck the melaphyr is believed to form flows interbedded with the conglomerate series. At Brighton the melaphyr appears to be intrusive. At Brookline and Newton there are many examples of igneous intrusion, where the igneous element is probably melaphyr, but the writer does not agree with Burr that all the melaphyr in this region is intrusive. Pebbles of melaphyr in the conglomerate indicate that surface flows also occurred.

Metamorphism. The rocks of the Boston Basin are often said to be practically unmetamorphosed. Crosby, for example, states that in spite of the extent to which the rocks have been sheared, folded, and faulted there has been little or no regional metamorphism with the development of an indigenous micaceous element (n, p. 504). There are, however, abundant signs of incipient metamorphism that are worthy of notice.

In almost every outcrop of the coarser members of the series planes of schistosity and cleavage are developed, which are often so perfect as to simulate stratification. Sometimes two or more directions of

schistosity are developed, but in such cases the strikes of the several planes are fairly uniform while the dips differ. The prevalent strikes of the shear planes are northeast or east-northeast and the dips, as a rule, are steep northerly.

While it is true that there is comparatively little secondary development of the micaceous element, it often happens that rocks containing a large number of felsite pebbles of fine grained, homogeneous character and greenish color, assume an unctuous appearance and feel. Such rocks have been described by Crosby in his earlier papers as pinite conglomerate. Where felsitic pebbles and finer material constitute the main elements of the conglomerate the rock is found to shade by almost imperceptible stages into felsite breccia and thence into compact felsite. Such gradations are to be observed at several localities, notably at Medford, Mattapan, Hyde Park, and South Natick. The impression left upon the observer after a study of such localities is that they represent cases where the matrix and pebbles or fragments consisting of one and the same kind of rock have been gradually welded by dynamic metamorphism into a compact mass entirely similar to the original rock. That such a type of metamorphism may be found among rocks of this character has been shown by Dutton in his account of the volcanic conglomerates of the High Plateaus, previously quoted (page 116).

The pebbles of the conglomerate in many localities are flattened, elongated, indented, and fractured, and often the matrix presents the appearance of flow structure. Sometimes open spaces have been left at the ends of the pebbles by the movements induced by the shearing forces. Later infiltrations have filled the cavities thus produced with quartz or calcite. The occurrence of such pebbles bears evidence of the presence of forces of deformation. The localities where they occur, if carefully searched out and correlated in zones, would indicate the position of the axis of deformation. No extended search with this idea in mind has been made by the writer, but the observations at hand tend to show that the deformed pebbles occur in more or less well-defined bands, extending in an east-west or east-northeast-westsouthwest direction. For example, distorted pebbles occur at the outcrops near the railroad in Auburndale, West Newton and at the ledge on North Beacon Street in Brighton, where the so-called slate pebbles occur. Again, they are found in the ledges north of the railroad at Newton Center, in the vicinity of Chestnut Hill Reservoir and at the great quarry on Tremont Street in Roxbury.

Farther south they are found in the vicinity of the Arnold Arboretum, at Jamaica Plain, and farther east at Squantum. The zones thus roughly indicated have already been shown to represent areas of folding or dislocation and the occurrence of these distorted pebbles in such regions shows that their production was closely related to these movements.

One of the most conspicuous features of the conglomerate is the remarkable development of joints. The latter usually occur in two main systems approximately at right angles to each other and having approximately north-south and east-west directions respectively, though the latter sometimes vary as much as twenty or thirty degrees on either side of these positions. Their dips are almost invariably steep, often vertical. Sometimes they are accompanied by joints of intermediate strike and dip. The noteworthy feature of these joints, aside from their constant occurrence and direction, is the smoothness and regularity of the surfaces produced by them. The rock is sliced as though with a knife, so that pebbles and matrix, hard and soft materials alike, are cut through with equal ease and precision. Similar joints in the conglomerate at Newport were long ago noted and described by C. H. Hitchcock (a, p. 113–114), who attributed their smoothness to the plastic condition of the rocks when they were formed. It is certain that their presence indicates conditions of great pressure or strain so that it is probable that their production was an accompaniment of the deformation process by which the rocks of the basin attained their present structure.

The Norfolk Basin.—*Literature.* The Norfolk Basin sediments have received much less attention in geological literature than those of either the Boston or the Narragansett Basin, largely on account of the extensive drift covering and the somewhat unsatisfactory nature of the exposures. The earlier papers of President Hitchcock and W. W. Dodge paid some attention to this area; the former, from the red color of the rocks, suggested their equivalence to the Old Red Sandstone. Crosby, in his Contributions to the Geology of Eastern Massachusetts, touched upon the Norfolk Basin sediments and expressed the opinion that they are synchronous with the rocks of the Boston Basin, which he then believed were Primordial. Later work by Crosby and Barton (1880) established the connection of the Norfolk Basin sediments with those of the Narragansett Basin and called attention to the existence of certain casts of tree trunks of Carboniferous age in the vicinity

of the village now known as Pondville. A few years later (1894) Woodworth described a fossiliferous section in the railroad cutting three-quarters of a mile north of the station at Canton Junction. The section at this locality had previously been noted by Dodge in the paper already cited (Dodge, a, p. 414). In his report on the Narragansett Basin (1899) Woodworth gives some account of the Norfolk Basin rocks and speaks more particularly of the section at Pondville. The latest and most extensive account of the rocks of this basin is found in the paper by Crosby (1900) entitled The Blue Hills Complex. To this paper the writer is indebted for much of the data used in the present discussion.

Form of the Basin. The Norfolk Basin extends northeast from Sheldonville, Massachusetts, where it joins the Narragansett Basin through a narrow pass (Franklin VI, LM 18–20), about twenty miles to Great Pond in Braintree, where it apparently ends. The general form of the basin, as shown in Figure 8 (p. 230) is a relatively narrow trough decreasing in width toward the northeast. It is approximately two miles wide where it is crossed by the Providence Division of the New York, New Haven, and Hartford Railroad; in the longitude of Ponkapoag Pond it is a mile and a half in width and eastward it narrows rapidly so that in the vicinity of Great Pond it is certainly not more than half a mile wide (Crosby, n, p. 467).

The Northern Boundary. The eastern portion of the basin immediately south of the Blue Hill Range is the only region where the northern boundary of the sediments can be located with any degree of precision. Elsewhere the drift cover is so complete as to render its position uncertain. The marginal rocks in the vicinity of the Blue Hills consist of very coarse accumulations styled by Crosby the "giant conglomerate," composed of boulders one or two feet in diameter and sometimes even three or four feet in diameter, usually well rounded or water worn (ibid., p. 471). Fine exposures of the rock occur *in situ* on the steep cliff-like slope 600 to 1,000 feet west of the junction of Randolph Avenue and High Street (Dedham VII, D 18) and at the "Streamside Ledge" half a mile east of the same point. At each of these localities the main feature of the rock is the abundant occurrence of boulders composed of the Blue Hills porphyry; other types of pebbles occur but no pebbles of felsite flows or of the normal granite (ibid., p. 471–473). Dips are not well shown by the conglomerate but occasional sandy or shaly bands indicate a southerly direction varying from 70° to 90° (ibid., p. 468). From alteration in the porphyry and from pebbles in the adjacent conglomerate

Crosby concludes that before the deposition of the latter the quartz porphyry was deeply oxidized, wholly at the surface and along the joints farther down, and that the superficial oxidized portion was worn away to provide material for the conglomerate, down to the mottled zone (one of the stages noted in the alteration of the porphyry), which was covered and thus protected from further oxidization (ibid., p. 475). According to this view the giant conglomerate forms the basal member of the Norfolk Basin series and rests in sedimentary contact upon the Blue Hills porphyry, from which it was largely derived.

The Streamside Ledge has not been visited by the writer but he has penetrated westward from the reference point named, certainly as far as the distance indicated by Crosby, though he cannot be sure that he has visited the identical outcrop. The south slope of Bear Hill down to the stream is strewn with boulders and masses of rock of varying sizes up to twenty feet or more in their greatest dimensions. Masses of conglomerate thirty feet in length appear nearly flush with the slope of the hill, but with so many boulders of varying size all about, there seems to be no certainty that even these large masses are in place, though some of them appear to be. The coarseness of the conglomerate is probably all that Crosby claims for it, though the largest boulders noted by the writer did not much exceed two feet in diameter, and these were largely subangular. A careful search was made among the pebbles of the rock for material resembling the Blue Hills porphyry, but with the exception of a single small and doubtful mass no such rock was found and no outcrop showing the contact of the conglomerate with any of the granitic rocks of the region was seen. On the other hand the prevailing rock among the pebbles is a fine grained granite, with a pinkish color and unlike the ledges and specimens of the Blue Hills prophyry studied by the writer. Moreover, many of the felsitic rocks of the Boston Basin are represented both in the pebbles and in the matrix of the conglomerate at this place, and, in addition, dark porphyritic rocks resembling some facies of the amygdaloidal melaphyr are represented. In one case a composite boulder contained a large boulder of granite and a basic scoriaceous pebble with phenocrysts of feldspar near the margin.

Among the large conglomerate masses near the northwest end of Great Pond and in a single low-lying ledge about a quarter of a mile southeast of Ponkapoag Pond (Dedham IV, Y 27) some boulders resembling the Blue Hills porphyry were found by the writer in the conglomerate, but samples collected and compared with numerous

specimens of the rock in question now in the students' collection of the laboratory of advanced geology at Harvard University were not satisfactorily identified. While, therefore, the writer is not prepared to deny the existence of pebbles of the Blue Hills porphyry in the conglomerate of the Norfolk Basin, his observations have not convinced him of its presence. Moreover, the fact that both along the south slope of Bear Hill and at the northwest end of Great Pond the conglomerate is broken into large masses that cannot certainly be said to be *in situ* seems to indicate that the conglomerate is not in simple sedimentary contact with the igneous rocks to the north, but that a zone of displacement exists along the northern border of the sediments. The fact that the southern base of the Blue Hills is bordered largely by low land occupied by swamps, streams, and ponds is not trustworthy evidence but it is at least favorable to the idea of a zone of dislocation.

The Sedimentary Series. The most continuous exposure of the beds of the sedimentary series is found in the rocky ridge already mentioned, east of the Neponset River. The northernmost exposures display the giant conglomerate with boulders two and a half feet long and one and a half feet wide, accompanied by pebbles eight or ten inches in diameter, all somewhat rounded. Outcrops along the ridge are frequent for a mile or more south to Pecunit Street and show a rapid gradation from the coarse conglomerate through finer conglomerates and grits to sandy red slate, showing beautiful cross-bedding, mud-cracks, and ripple-marks. According to Crosby the dips are steadily southward at angles varying from 70° to 90° (Crosby, n, p. 468). The writer's observations, however, show a strike of N 60°–70° E and a dip varying from a steep northerly, almost vertical inclination at the north end of the ridge to 70° or 80° S near the shale at the south. The attitude of the ripple-marks and mud-cracks shows that the strata are not inverted. East of this ridge the exposures all show a tendency to red color but farther to the southwest grayish and greenish rocks appear as well. Other scattered groups of outcrops occur east of Ponkapoag Pond, north of Canton Junction, at East Walpole, and farther southwest toward Wrentham. The most interesting of these occurrences is to be found in Pierce's Pasture at Pondville, described by Woodworth. Here the Carboniferous beds rest on hornblende granitite and dip steeply north in the form of a closed and puckered syncline, pitching eastward (Woodworth, d, p. 136). The basal member of the series here is arkose, which apparently rests upon the granitite from which it was derived and which it closely resembles.

The section north of Canton Junction contains fossiliferous shales and a band of limestone (Woodworth, b, p. 147).

General Structure. According to Crosby there is no repetition of the basal conglomerate and the dips are all southerly, so that the structure of the eastern portion of the basin is a monocline (n, p. 469). He considers that the western part of the Blue Hill Range, together with the region occupied by the Norfolk Basin sediments, constitute a fault block that has been tilted south, the boundary faults lying along the north side of the hills and the south side of the sediments respectively (n, p. 500–501). The writer's observations have led him to propose some modifications of these views. A quarter of a mile southeast of Ponkapoag Pond occurs a low ridge-like mass of conglomerate about forty feet long, with an east-west trend, and composed of rounded and subangular pebbles ranging in diameter from six inches to two feet. This is the outcrop above mentioned (page 221) where the pebbles appeared to resemble the Blue Hills porphyry. North of this exposure and east of the pond there are numerous outcrops of red sandy shale with fine conglomerate that intervene between the conglomerate immediately south of the Blue Hills at Houghton's Pond and the rock in question. If the latter be considered as really in place it must indicate a repetition of the strata by faulting or folding, or else it belongs in a different horizon from the other coarse conglomerate — an unlikely supposition in view of the gradation of the sediments displayed by the rocky ridge at the west. The apparently uniform southerly dips would perhaps justify the idea of a monocline, broken by strike faults, in the eastern part of the area, but the structures indicated at East Walpole and at Pondville show that such is certainly not the case in the southwestern part of the basin. The limited outcrops at the former locality show intense folding with some faulting while at the latter place the same features are more clearly displayed. Moreover, the basal sediments exposed at Pondville are arkoses and none of the immediately overlying beds can be compared in coarseness with the heavy conglomerates of the northern border. In the Narragansett Basin arkoses occur near the base of the series and heavy conglomerates appear high in the section.

As in the case of the Boston Basin the question of climatic conditions is raised by the occurrence of arkose at Pondville. The discussion of its climatic significance is reserved for the succeeding chapter but it may be stated here that the conditions favorable for the production of arkose are unlikely to be favorable for the production of heavy, water-worn comglomerates. It therefore seems improbable

that the heavy conglomerates of the northern border and the arkoses of the southern border were formed at the same time. The basal character of the arkoses cannot be doubted, since they rest upon the granitite from which they were derived. The basal character of the heavy conglomerates at the north, on the other hand, does not seem to the writer to be clearly established, though it must be admitted that they lie beneath a great mass of grits and sandstones, which, from the attitude of included ripple-marks and mud-cracks, show that there has been no inversion of the strata. The writer is therefore inclined to place the conglomerate higher in the section than at the base. Under this interpretation the structure of the sediments along the northern border may be regarded as monoclinal but faulted down along that line. It is highly significant in this connection that the first sediments encountered on the north side of the Blue Hill Range toward the west are arkoses overlain by slates of somewhat similar appearance to those that overlie the arkose at Pondville. Under this interpretation it may be conceived that the arkoses and overlying sediments of the Narragansett Basin were once continuous over the present site of the Blue Hill Range and that the basins became separated by the down-faulting of the Norfolk sediments along the south side of the present range. The steep northerly dip, changing to southerly, of the rocks along the northern border of the basin may be explained as due to drag, with a slight overturning on the north.

On the other hand, the coarseness and known distribution of the conglomerate seems to indicate a local source for the materials and it is natural to turn to the hills immediately at hand as the most probable region from which the boulders could have been derived. Crosby, in his description of the Streamside Ledge, states positively that pebbles of the Blue Hills porphyry occur in the conglomerate of that locality and that the contact of the conglomerate with the igneous rocks on the north is sedimentary. According to his view the existing basins now occupied by Carboniferous rocks were not outlined at the time when deposition began (n, p. 464) but boundary faults developed during the progress of deposition (ibid., p. 501). He conceives that deep faults occurred along the north side of the Blue Hills Range and farther south along the boundary between the sediments and the granites; that the block thus formed comprised the mass of the Blue Hills and the area now occupied by the sediments, and that this block was gradually tilted southward so that a growing depression was formed, in which the sediments were deposited (ibid., loc. cit.). The giant conglomerate was formed by the action of vigorous surf on the

bold shore thus produced along the south side of the hills (ibid., p. 500). Under this supposition it would seem that at least equally coarse conglomerate should have formed on the north side of the hills, where the fault scarp was developing. Crosby accounts for its absence by stating that the sediments on the north side were thrown down by the fault and that the basal beds are not exposed (ibid., p. 501). This idea seems hardly credible, since, in the case of a growing fault of the magnitude required by the hypothesis, a talus of coarser materials, rearranged, perhaps, by aqueous agencies, might be expected to accumulate along the fault scarp. The successive slips of the growing fault might produce fractures or faults in the debris accumulations similar to those noted by Gilbert and others in the Great Basin region of the United States, but it is difficult to see how such accumulations could be carried out of sight by the very faults to which they owed their existence. The occurrence of arkose, too, on the north side of the hills, indicates that the basal sediments are not concealed, as suggested by Crosby, but that they lie in sedimentary contact upon the adjacent granites.

If the fault be conceived as occurring on the south side of the range the presence of the conglomerate in that particular region may be more satisfactorily explained. It may very well be supposed that the period of relative quiescence in which the arkosic materials were being developed was terminated by movements of uplift or by climatic changes of such character as to permit the rapid deposition of these materials without further disintegration. Thus arkoses and overlying slates and conglomerates may have been laid down in order. Then the fault may have developed along the southern edge of the Blue Hills. If the giant conglomerate does not contain bona fide pebbles of the Blue Hills porphyry, it may be considered as part of a layer, perhaps eroded away at the north, preserved by down-faulting against the porphyry. But if Crosby's contention be allowed, that boulders of the porphyry do occur plentifully in the giant conglomerate, a supposition apparently favored by the doubtful cases noted by the writer, the conglomerate may be considered as a talus of coarse waste developed along the growing fault scarp and worked over by aqueous agencies so that it became more or less water worn. In such a case it might be expected that, as the fault progressed, the successive slips would cause the growing accumulation to become fractured and displaced and perhaps broken into minor blocks. Evidence of this character is bountifully supplied by the great blocks of conglomerate that lie immediately south of Bear Hill and at the

northwest corner of Great Pond. It might be expected also that there would be some evidence of igneous action along the line of a deep and growing fault. Evidence of this kind is not entirely wanting, for the writer found among the conglomerates on the southern slope of Bear Hill igneous impregnations quite similar to those noted at Walnut Hill and elsewhere in the Boston Basin (see page 157).

Furthermore, it might be presumed that some representatives of the Blue Hills rocks would occur on the north side of the range, if the latter were exposed to erosion on the south side. Since the fault scarp faced south, however, and the northern slope may be supposed to have been more gentle, it would not be expected that so great a proportion of these rocks would appear in the conglomerates. Careful search among the pebbles of the latter on the north side of the ridge has thus far failed to produce any types that have been definitely assigned to the Blue Hills porphyry, but it has been shown (page 168) that specimens, collected by H. J. Wiswell from the Roxbury Conglomerate in the vicinity of the Bird Street Station, bear a striking resemblance to certain facies of the rock in question. Under this supposition, then, the Blue Hills region may be conceived as a fault block of the Great Basin type, that was uplifted during the deposition of the Carboniferous rocks thereabouts and perhaps partly or entirely buried by subsequent accumulations of sediment.

The relations of the southwestern part of the basin to the eastern portion are not clear. From the limited exposures it appears that intense folding has occurred, followed by transverse faulting. These features are especially well shown at Pondville. The difference in the appearance of the strata of the eastern section seen in the rocky ridge east of the Neponset River and the rocks of the southwestern section seen at East Walpole is so striking that it suggests a line of separation corresponding in direction to the transverse faults noted farther southwest. These faults at Pondville occurred later than the folding. It is possible, therefore, that previous to this transverse faulting the eastern portion of the basin may not have been an area of deposition and that the sediments now found in that region are younger than those farther southwest. The evidence, however, is insufficient to warrant any definite conclusions to that effect.

Thickness. In the eastern portion of the area the section afforded by the rocky ridge east of the Neponset River shows no apparent repetition by folding or faulting and there is almost continuous exposure of the rocks for more than a mile. According to Crosby's figures the aggregate thickness of the series is at least 5,000 feet and

possibly nearly 10,000 feet (n, p. 468–469). The lower figure is certainly a safe minimum considering the length of exposure and the steepness of the dip (90° to 60°). According to Woodworth's figures the thickness of the section exposed at Pondville is 250–300 feet (d, p. 136). On the supposition that the giant conglomerate does not represent the base of the series the thickness of the Pondville rocks may be added to the minimum figure given, making 5,250 to 5,300 feet. It is probable, however, that the actual thickness of the Norfolk Basin sediments greatly exceeds this figure, for at the Canton Junction ledges a mile and a half southwest of the southern end of the ridge above mentioned the rocks still maintain the southerly dip and present different facies from those farther north. The structure and thickness of the Norfolk Basin sediments make it probable that they were continuous, at least in part, with the sediments of the Boston Basin, though no definite correlation is now possible.

The Southern Boundary. On account of the same features, Crosby believes that the southern boundary of the Norfolk Basin, in its northeastern part, is a profound fault, with the downthrow on the north, that extends northeast and cuts out the gray beds east of the Canton Junction locality (Crosby, n, p. 470). So far as the writer's observations have gone they are in harmony with Crosby's view in this respect. There is no locality where the boundary can be observed and its position is largely conjectural, but there appears to be no place where the lower beds at the north rise again to the surface except at the locality southeast of Ponkapoag Pond where the ledge of coarse conglomerate was noted (page 221), and here the relations seem to indicate faulting rather than folding. In the southwestern part of the basin, however, the only region that shows the actual southern border of the sediments is the Pondville area and there the beds rest in sedimentary contact upon the granitite without the intervention of a fault.

Relations to Igneous Rocks. Crosby has pointed out in earlier and later papers that the Norfolk Basin sediments are not associated with contemporaneous lavas and that they are practically free from dikes (Crosby and Barton, p. 417; Crosby, n, p. 499), the only dike thus far discovered being the one exposed in the section along the railroad north of Canton Junction. Woodworth has suggested that the apparent absence of these features may be due to the extensive covering of drift and alluvium and that they may in reality be more abundant than is generally supposed (b, p. 148). The occurrence of the igneous impregnations in the conglomerates on the south side of Bear Hill,

observed by the writer and mentioned (page 162) lends support to this view.

Metamorphism. In the northeastern part of the basin the rocks display shearing in much the same degree as do those of the Boston Basin but there is comparatively little evidence of dynamic metamorphism. The occurrence of ripple-marks and mud-cracks in the Pecunit Street ledges, comparatively undisturbed, indicates the slight extent to which these rocks were affected.

In the southwestern part, on the other hand, a high degree of metamorphism has been attained. The ledges between Walpole and East Walpole and also farther southwest show a marked development of secondary mica and in some cases of chlorite. Pebbles in the conglomerates are marked with pressure striations and are sometimes deformed and indented, while the finer sediments have become highly schistose. The contrast in degree of metamorphism between the northeastern and southwestern sections may be partly explained by their difference in structure; but it is probable too that the southwestern sediments were under a greater pressure of superincumbent strata than was the case with the northeastern sediments, since the former are known to be basal while the latter are probably higher members of the series.

Summary. The Norfolk Basin sediments occupy a trough-like depression, narrowing toward the northeast. Field evidence shows that it is divisible into two areas, which present different types of structure, the line of separation being probably a transverse fault, following roughly the present valley of the Neponset River south from Green Lodge. The southwest area is characterized by closely folded strata, overturned southward, the best exposures being seen at Pondville. Transverse faults are numerous in this area, but longitudinal faults are not so clearly indicated. The relations of the arkose to the granitite show that at Pondville at least the southern boundary of the basin is a true sedimentary contact.

The northeastern area is characterized by monoclinal structure with no clear evidence of folding. The northern boundary of the basin in this region is believed by Crosby to be sedimentary, the coarse so-called basal conglomerates resting directly against their parent ledges, and owing their formation to the progressive southward tilting induced by the growth of a deep fault on the north side of the Blue Hills, during the period of deposition of the sediments. The present writer, however, regards the basal arkose exposed at Pondville as the normal base of the sedimentary series of the region and believes that

it was probably formerly continuous or contemporaneous with the arkose north of the Blue Hills and at Dedham. He believes that the absence of the giant conglomerate along the north base of the hills is not due to concealment by a fault but either to erosion or to non-deposition, the true basal sediments being the arkoses there exposed. He considers that the northern boundary of the basin is a fault, with downthrow to the south, along the southern flank of the Blue Hills. He regards the giant conglomerate as either an uneroded remnant of a former more extensive mass now preserved by down-faulting, or as a local deposit rearranged by aqueous agencies and accumulated along the base of a fault scarp that developed progressively during the period of deposition of the sediments, the fractured and broken masses of conglomerate and the igneous impregnations bearing witness to the successive slips of the growing displacement. As regards the southern boundary, the writer agrees with Crosby that a deep fault with downthrow on the north appears to be demanded by the apparent monoclinal structure. On the supposition that the arkoses form the real base of the series, and that the fault which permitted the formation of the giant conglomerates began during the period of deposition, the sediments of the eastern portion of the basin are probably more recent than part, at least, of the Pondville series.

The occurrence of igneous impregnations in the conglomerate lends support to the view that igneous rocks play a more important part in the history of the basin than is generally supposed.

The rocks of the eastern part of the basin are relatively unaltered, while in those of the southwest portion a high degree of metamorphism has been attained.

THE NARRAGANSETT BASIN.—*Literature.* The Narragansett Basin has been the subject of a considerable literature, of which a bibliography may be found in Professor Woodworth's report (d, p. 212–214). The writer has not attempted any general study of this material but has confined his attention to the monograph entitled, Geology of the Narragansett Basin, the joint work of Shaler, Woodworth, and Foerste, and to a few lesser papers.

Shape and Size of the Basin. The Narragansett Basin, as shown in Figure 8, is a somewhat irregular trough extending north from the coast of Rhode Island into Massachusetts, where it bends east towards the Atlantic near Duxbury, Scituate, and Cohasset, and comes within about six miles of the sea (Shaler, et al., p. 7). The eastward bend is made near the northeast corner of the state of Rhode Island and in

that vicinity the narrow trough of the Norfolk Basin joins the Narragansett Basin through the pass at Sheldonville, Mass. On the south

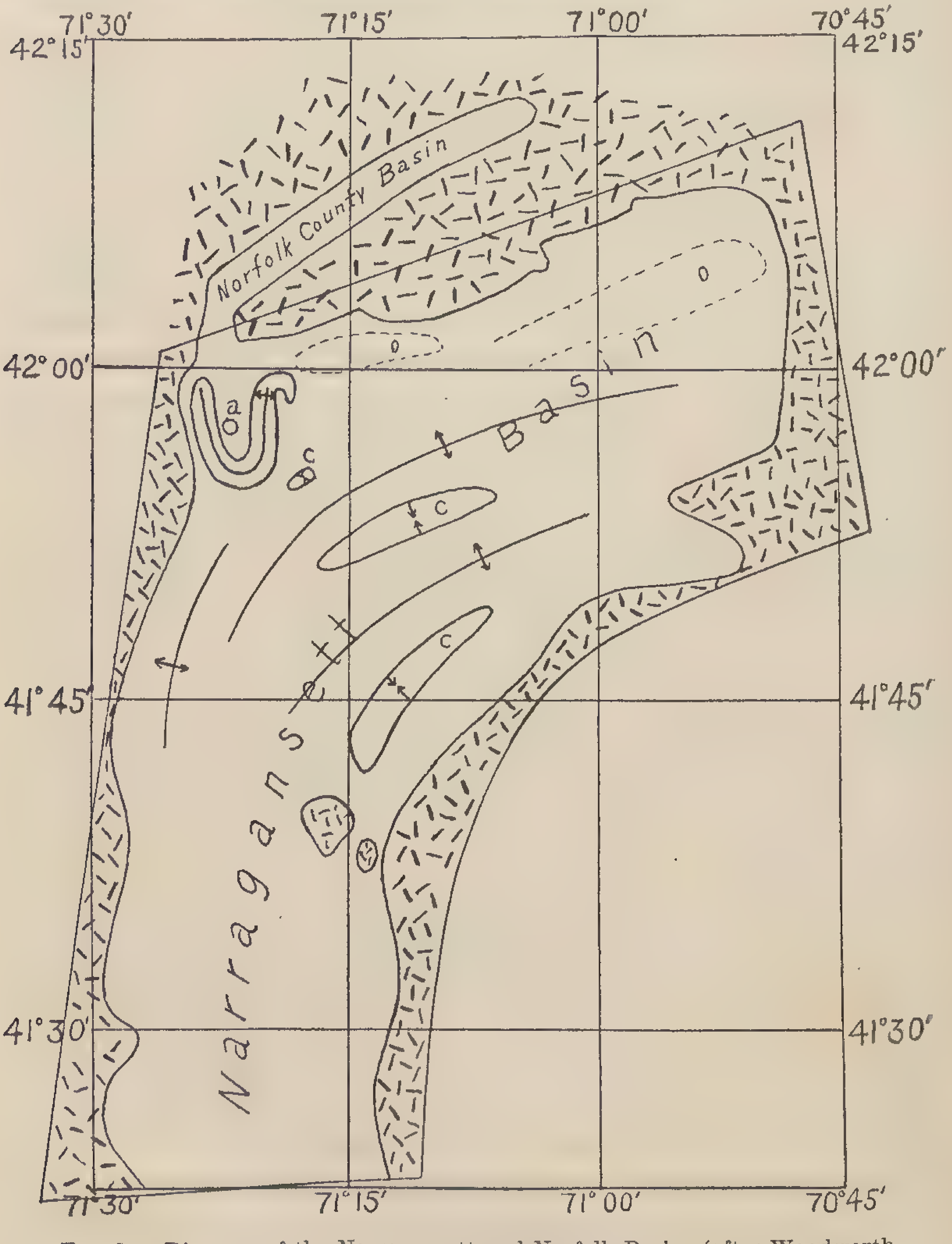

FIG. 8.— Diagram of the Narragansett and Norfolk Basins (after Woodworth, d, p. 121).
a. Fault block at Hoppin Hill.
c. Synclines containing coarse conglomerates
o. Synclines near the border.
Arrows indicate direction of dip.

the basin is partially separated from the sea by a constriction formed of ancient, highly metamorphosed, stratified rocks and a variety of intrusions, together with some granitic areas which are probably of great age (Shaler et al., p. 7).

The north-south extension of the Narragansett Basin, including the Norfolk Basin, the axis of greatest length, is about fifty miles. The east-west diameter, from the western part of Cumberland, R. I., to Scituate, Mass., is about thirty miles. Although its outline has many irregularities, the basin has in general a rudely curved form, concave on the southeastern side (ibid., p. 8).

Boundaries. The maps of Woodworth and Foerste in the monograph above mentioned show that the boundaries of the present sedimentary area are generally true sedimentary contacts and are not marked by faults to the degree that seems probable in the case of the Boston and Norfolk Basins. Faults of the normal basin range type do occur at several places along the borders of the basin but their usual direction is north-south, with the downthrow on the east or west (Woodworth, d, p. 132), while the dominant direction of the probable faults in the Boston and Norfolk Basins is east-west, with the downthrow on the north or south. The irregularities of the borders of the Narragansett Basin are due largely to these faults.

Sedimentary Series. The Carboniferous rocks of the Narragansett Basin have been divided into four groups by Woodworth in the northern part of the field and by Foerste in the southern area. The northern rocks have somewhat different facies from those of the southern area but the sediments of the two regions are believed to represent synchronous deposition. The following account is taken from Woodworth's table (d, p. 134).

In the northern area the lowest member, called the Pondville group, consists of quartz conglomerates and arkose and has a thickness of about 100 feet. The Wamsutta group, consisting of conglomerates, sandstones, arkose, shale, or slate, and beds of quartzite, accompanied by felsites, felsite breccias, and conglomerates, overlies the Pondville group, and has a thickness of about 1,000 feet. Some of the members carry Calamites. The characteristic color of the series is red, but locally brown and green colors occur. Above the Wamsutta group come 10,000 feet of alternating beds of fine and medium conglomerates, pebbly sandstones, sandstones, and shales, with some coal beds. This group, known as the Rhode Island Coal Measures, has produced a considerable flora and fauna, the latter consisting largely of insects. The prevailing colors are black, blue, green, gray, and locally red.

The highest member of the series is the Dighton Conglomerate, 1,000 to 1,500 feet thick, consisting mainly of coarse quartzite and granitic pebble conglomerates, with finer conglomerates and sandstone.

In the southern area the basal beds present the same general characteristics as those given for the Pondville group. The Wamsutta group, however, is not traceable south of Providence. It is probably represented by lower strata of the Kingstown series of Foerste. The Kingstown series, consisting mainly of sandstones and conglomerates, with coal shales, and the Aquidneck shales of Foerste, composed chiefly of shales with coal beds, when traced northward, appear to form equivalent sections beneath the Dighton group, one on the eastern, the other on the western side of Narragansett Bay. Both extend downward to the basal beds. The Purgatory Conglomerate forms the upper member of the Carboniferous series in the southern part of the basin. It consists mainly of coarse quartzite pebbles, usually much elongated and indented (Plate 3, B). It is probably, but not certainly, identical in all parts of the field, lying in synclines above the coal measures.

Fig. 9.— Outline of the structure of the Narragansett Basin (after Shaler et al., p. 27).

General Structure and Thickness. The structure of the Narragansett Basin has been carefully worked out by Woodworth and Foerste in their monograph. In the present paper the intention is to give only the main outlines as indicated by them and by the accompanying report of Shaler. The broader structural features are relatively simple and consist of a system of folds with their axes parallel to the borders of the basin. There are three main synclines in which the Dighton group appears, the Attleboro syncline on the north, the Great Meadow Hill trough through the middle of the basin and the Swansea syncline on the south. The central syncline is nearly symmetrical, with relatively low dips, while the synclines parallel with it on the north and south have their axial planes inclined away so that

the sides of the synclines facing the middle area are nearly vertical (Shaler et al., p. 27). These main features are indicated in Figure 9, taken from Shaler's account. In some parts of the basin there has been further folding and some faulting. At Hoppin Hill in North Attleboro a small area of profound dislocation has brought the underlying granitite, Cambrian and Lower Carboniferous strata to the surface (Woodworth, d, p. 121). The number of great folds in the basin is few, but the great mass of sediments is here thrown into folds quite equal in dimensions to those of the Appalachian region in Pennsylvania. From axis to axis of the same kind is a distance of upwards of six miles. With dips often 45° or more, folds of so great breadth indicate a great thickness of strata, of which there cannot be less than 12,000 feet now remaining (ibid., p. 122–123).

Relations to Igneous Rocks. In the Narragansett Basin igneous rocks appear in association with the Wamsutta group. Dikes of diabase occur near North Attleboro which are commonly vesicular for a distance of one to three feet from the upper surface, and sometimes the lower surface is amygdaloidal, but there is no evidence that the diabase flowed out as a contemporaneous sheet (ibid., p. 152). In the same region an acid series of igneous rocks of felsitic and granophyric texture is intimately associated with the Wamsutta group. The felsite occurs frequently at stratigraphically higher horizons than the intruded diabase, is marked by a definite flow structure, and is often accompanied by a crumpling of the layers (ibid., p. 154). "The rapid thickening of the sandstones and conglomerates toward the northwest corner of the present area, the felsite with definite flow structure, the gray ash beds or Attleboro sandstone, the agglomerates of felsitic material, and the associated conglomerates composed in large part of felsitic pebbles all point to a volcano or volcanoes existing in this field in Carboniferous time" (ibid., p. 155).

Metamorphism. According to the accounts of Shaler and Woodworth the rocks of the Narragansett Basin have suffered less from metamorphism than was formerly believed by most geologists. It is true that in some parts of the area the rocks have become highly metamorphosed but the regions thus affected are, on the whole, rather localized. The most extensive of these regions begins near Pawtucket and widens as it extends south toward the sea in Narragansett Bay, the most pronounced effects being observed along the western boundary. The transition from this highly metamorphosed zone to the comparatively unaltered rocks on the east is so abrupt that one is led to believe that an intermediate zone of considerable width has been concealed by a fault (Woodworth, d, p. 119).

On the eastern side of the basin, south of Tiverton, a high degree of metamorphism has been attained. At Fogland Point the conglomerate pebbles have been elongated, flattened, indented, and striated under pressure, and there has been an extensive development of mica. The shape of the pebbles indicates that they must have been more or less plastic when deformed, yet the groups of tension cracks, some of them passing entirely through the pebbles, indicate that the pressure under which deformation took place was not sufficient to induce perfect plasticity. Plate 5 shows typical ledges of the metamorphosed conglomerate. The Purgatory Conglomerate, already mentioned (pages 165 and 168), farther south, shows similar characteristics, but there the pebbles are much larger. In both these localities the elongation of the pebbles must equal or exceed 50 per cent of the original diameter on the given axis, as stated by Shaler (p. 17). At Purgatory, near Newport, the writer observed a pebble or boulder in the conglomerate that measured nine feet in length and three feet in width, but some of these boulders are described by Hitchcock as attaining a length of twelve feet (C. H. Hitchcock, a, p. 113–114).

Farther within the basin the rocks have been only slightly affected. In a quarry half a mile south of the intersection of Thatcher and County Roads at Attleboro, opened in the rocks immediately below the Dighton conglomerate near the top of the syncline, ripple-marks, rain-imprints, and worm-trails appear on the surface of shaly beds that are now standing nearly vertical. Woodworth, speaking of these features, remarks that the "preservation of this record at this locality, where the beds are now vertical, indicates that locally, at least, metamorphism in the Rhode Island coal field has not gone so far as is commonly believed. The condition of the imprints shows that in the folding of the strata on this horizon, at least, there was no widespread shearing of layer over layer, which in other localities is usually marked by slickensides or the appearance of 'grain'" (d, p. 178).

Summary. (1) The Narragansett Basin sediments occupy a somewhat irregular trough about fifty miles long and thirty miles wide, rudely concave toward the southeast.

(2) The boundaries are not determined in the main by faults but are usually sedimentary contacts with the surrounding rocks.

(3) The sedimentary series consists of arkoses, conglomerates, sandstones, and fossiliferous shales, with some coal beds.

(4) The arkoses form the basal members and the highest beds are heavy conglomerates.

(5) The structure shows a system of folds of Appalachian type and dimensions — a broad syncline in the middle, with steeper synclines on either side, overturned toward the border.

(6) The preserved thickness is at least 12,000 feet.

(7) Igneous rocks as basic intrusives or acid effusives are associated with some of the lower members of the series.

(8) Metamorphism has been intense in certain areas but in general its effects have been slight.

THE HARVARD CONGLOMERATE.—*General Description.* The only accounts of the conglomerate in this region found by the writer are by L. S. Burbank (1876) and Crosby (1880). The rock has a limited area of wedge-like form, broadest at the north, where it is only 400 or 500 feet in width, and tapering southward, where it dies out after two miles. According to Burbank the conglomerate is associated with soft argillite and chloritized slate and all are interstratified with the inclosing gneiss and coincide with the dip and strike of the latter. The pebbles of the conglomerate consist chiefly of a gray quartzite unlike any neighboring rock (Burbank, p. 224–225).

Structure. The writer's somewhat hasty observations in the field show that the conglomerate is interbedded with grit and sheared sandstone. The strike is north-northeast and the dip is steep westerly, nearly vertical. On the west the conglomerate is bordered by phyllite, while a short distance east the gneiss appears. In conversation with the writer, Professor Emerson, who has studied the Harvard section, expressed the opinion that the gneiss and phyllite there exposed form part of the northeast extension of the similar rocks at Worcester, which he regards as Carboniferous. The structure at Worcester, as made out by Perry and Emerson, is an eroded anticline with a symmetrical syncline on the east (Perry and Emerson, p. 49). East of this syncline lies the great anticline of older rocks that extends northeast from Rhode Island into Massachusetts through Douglass, Uxbridge, Sutton, and Northbridge (ibid., p. 155–156).

Possibly the Harvard Conglomerate may represent a portion of the eastern limb of the syncline, as made out by Perry and Emerson. The tapering wedge-like form of the conglomerate mass is suggestive of faulting. Perhaps the conglomerate may be a lens in the phyllite formation, but if so the northern end of the lens is not exposed, to the writer's knowledge.

Thickness. Since the dips are very steep the combined thickness of the conglomerate, with its interbedded grits and sandstones may

be as much as 300–400 feet in the widest portion. Southward the conglomerate apparently thins out.

Metamorphism. The highly fractured and metamorphosed condition of the conglomerate is described by both Burbank and Crosby, the latter deriving most of his information from the former. In the field two directions of schistosity were noted, one nearly parallel to the strike, with an easterly dip of about 40°, the other with a northeast strike and a more gentle southeasterly dip. A description of the principal characteristics of the pebbles has already been given (page 167). The suggestion is strong that the conglomerate was formed *in situ* by the disruptive action of the shearing and crushing forces upon layers of quartzite but the conglomerate cannot be traced along the strike into unaltered quartzite. Moreover, the resemblance of many of the fragments to water-worn pebbles is very striking. Some of the latter are broken and the pieces separated, while others are elongated into distorted lenses (Figure 10, A and B). On the whole the general impression left by a study of the rock is that it represents an original conglomerate, that has suffered dynamic metamorphism at a depth too slight to permit the production of much plasticity.

Summary. The Harvard Conglomerate forms a small wedge-shaped area extending two miles southwest from the vicinity through the town of Harvard. It strikes nearly north-south and has a steep westerly dip. Its stratigraphic position and age are uncertain but it may form part of the northeast extension of the eastern limb of the syncline in the Carboniferous rocks just east of Worcester, as worked out by Perry and Emerson. The most striking feature of the conglomerate is its brecciated, stretched, and generally metamorphosed appearance.

General Summary.—*Structure.* The Boston Basin is probably bounded by faults on the north and south and is characterized by eastward pitching folds, broken by faults.

The Norfolk Basin is divided into two areas, northeast and southwest. The northeast region is probably bounded on the north and south by faults and has a relatively simple monoclinal structure. The southwest area is characterized by folds and transverse faults. Its southern boundary is, in part at least, a true sedimentary contact.

The Narragansett Basin is bounded mainly by sedimentary contacts and is characterized by a system of large and relatively simple folds.

The strikes of the faults and of the axes of the folds in the Boston and Norfolk Basins are prevailingly east-northeast. The faults in the

southwest part of the Norfolk Basin and the folds and faults of the corresponding portion of the Narragansett Basin are prevailingly north-northeast.

Thickness. The thickness of the sedimentary series in the Boston

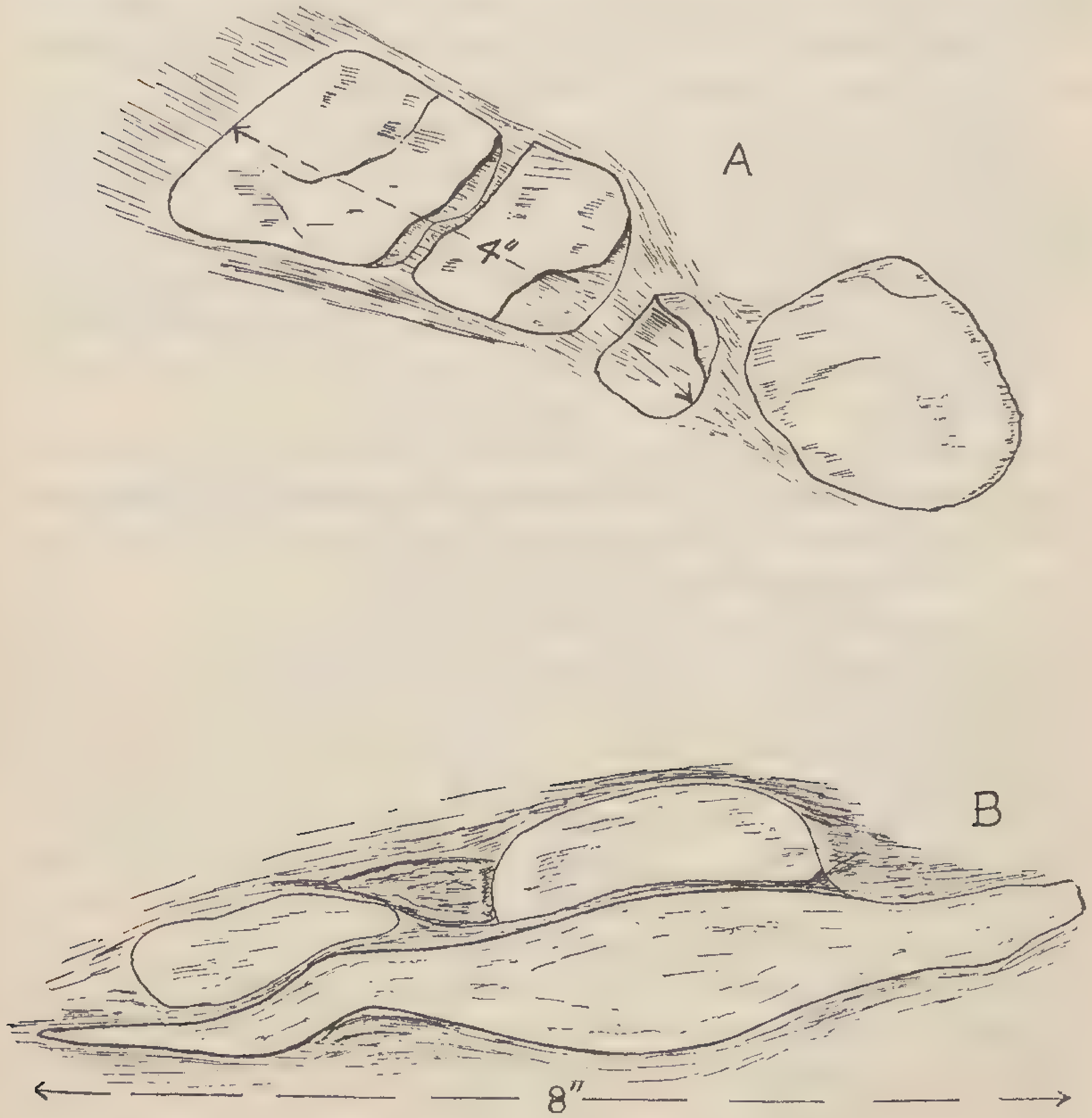

FIG. 10.— Deformed pebbles of the Harvard Conglomerate.

Basin may be as great as 5,300 feet. In the Norfolk Basin it is certainly equal to that figure and is probably considerably greater, perhaps nearly 10,000 feet. In the Narragansett Basin the structure requires a preserved thickness of 12,000 feet. In all these areas an unknown thickness of sediments has been removed by erosion, so that the original depth of the Carboniferous deposits in this region may have greatly exceeded even the largest of the figures given. The

structure and thickness indicate that the series was once continuous over the entire area.

Relations to Igneous Rocks. In the Boston and Norfolk Basins extensive eruptions of acid lava preceded the deposition of the Carboniferous series and are abundantly represented in the conglomerates. In the Narragansett Basin similar lavas occur in the Wamsutta group, one of the lower members of the series.

Basic lavas, intrusive or effusive, occupy an important place among the Carboniferous rocks of the Boston Basin. In the Norfolk Basin the only suggestion of their occurrence is the impregnation of the conglomerate observed on the south slope of Bear Hill, and at two other localities. The amygdaloidal and scoriaceous dikes of diabase in the Wamsutta group at North Attleboro are the only representatives of these rocks known in the Narragansett Basin, and these may be of later date.

Later dikes are numerous in the Boston Basin and are represented in the Norfolk Basin by the dike in the section north of Canton Junction. Dikes occur in the Narragansett Basin but are not so numerous nor so important as those of the Boston Basin.

Metamorphism. In all the regions under consideration metamorphism has occurred to a greater or less extent. In the Boston Basin it is confined chiefly to shearing, together with some deformation of the pebbles of the conglomerate. The tendency of zonal arrangement indicates a close relation between phenomena of metamorphism and the axes of the folds. In the Norfolk and Narragansett Basins areas of intensely metamorphosed rocks occur where folding and deformation have been most intense but a large portion of each of these regions has been only slightly affected.

Harvard Conglomerate. The Harvard Conglomerate is intensely brecciated and metamorphosed. It may be related to the Carboniferous rocks and structures worked out by Perry and Emerson in the vicinity of Worcester.

Hypotheses of Origin.

Statement of Problem.—*Thickness and Bulk of Sediments.* It has been shown that in the Carboniferous basins great accumulations of sediment have been formed. In the Narragansett Basin a preserved thickness of at least 12,000 feet is required by the present structure; in the Norfolk Basin probably 5,000 to 10,000 feet of beds are represented; in the Boston Basin the maximum thickness, including the slates as Carboniferous, may be as much as 5,300 feet.

The dimensions of the various basins as given in preceding pages are too indefinite to be of absolute value but they serve to give a general idea of the areal content of these regions. The average thickness of the sediment in the several basins has not been determined but it may be fair to assume that it is equal to at least half the maximum amount indicated by the figures just given. Assuming the area of the Boston Basin to be 125 square miles (see page 98), and the average thickness of the sediments, including the slates, to be 2,650 feet, or roughly half a mile, the bulk of the Carboniferous rocks included may be estimated at 62.5 cubic miles. Similarly, if the Norfolk Basin is assumed to be 20 miles long and to have an average width of 1.5 miles (see page 220), the area will be 30 square miles, and if the average thickness is assumed to be 3,750 feet, or approximately 0.7 miles, the bulk of the Norfolk Basin sediments may be estimated at 21 cubic miles. According to the figures given by Shaler (*cf.*, page 231), the Narragansett Basin is approximately 50 miles long and 30 miles wide, giving an area of 1,500 square miles. Assuming the average thickness to be 6,000 feet, or about 1.1 miles, the bulk of the Narragansett sediments is 1,650 cubic miles.[1] The total bulk of the Carboniferous rocks now preserved in the three basins, according to these figures, is 1,713.5, or roughly 1,700 cubic miles. When it is remembered that vast periods of erosion have intervened since the deposition of these rocks, and that an unknown but probably great proportion of the original mass has been thus swept away, it will be seen that the former land area which furnished the Carboniferous accumulations must have suffered intense erosion, during this deposition, and must have undergone important changes of form.

Local Character. The materials, of which this great sedimentary mass is composed, are mainly the same as the rocks now exposed around the borders of the basins. Noteworthy exceptions are the fossiliferous quartzite and muscovite-granite pebbles found in the conglomerates of the Narragansett Basin, to which reference has already been made, (page 164).

The Problem. The problem now to be considered may be stated interrogatively as follows:—What were the agencies, by which so great a bulk of local materials was removed from its parent rock and accumulated in the present areas, and under what conditions were the deposits made?

GEOGRAPHICAL CONDITIONS.—*Restoration of Strata.* One of the

[1] This estimate is slightly too large since the Norfolk Basin has inadvertently been included and is therefore counted twice. The final estimate is not materially affected.

first steps in the solution of such a problem should be the attempt at restoration of the geographical conditions of the time. The rocks of all three basins are now extensively folded and faulted and often dip at high angles. Originally they must have been nearly horizontal, or at least only slightly inclined, though in consequence of coincident subsidence of the floor of deposition, or because of varied conditions of sedimentation, the lower beds may have been of steeper inclination than the upper. If the present deformed floors of the several basins could be straightened out, the overlying strata would form a great mass, probably extending across the granitic areas now separating the basins and attaining a length of at least 60 miles and a breadth of 30 miles. The figures for thickness given above show that there would be under these conditions a diminution in the elevation of the restored mass northward from 12,000 feet to perhaps 5,000 feet or less. Since it is certain that great erosion has taken place over the entire area subsequent to the disturbance of the strata, it is probable that the limits of the restored mass would greatly exceed those above outlined.

The apparent northward diminution in thickness may be due either to original difference in the depth of the deposits or to erosion, for the floor of the northern sediments may not have been carried so far beneath the base-level of erosion as in the case of the southern sediments and a consequently greater proportion of the northern deposits may have been removed. The more marked development of overthrust phenomena in the northern basin, however, lends support to the idea that the sediments in that region never attained the thickness reached by the southern strata; for Willis has shown that in the Appalachian region the greatest faulting has occurred where the thickness of strata is not so great (Willis, a, p. 269).

Any restoration of the strata must include the restoration of the neighboring land areas from which their materials were derived. It has been shown (page 169) that the increasing coarseness of the Dighton or Purgatory Conglomerate toward the south, together with the increase in the percentage of quartzite pebbles in that direction, indicate the probable occurrence of land at the south, no longer extant, while the increase in quantity of muscovite-granite pebbles toward the north or northwest indicates that the muscovite rocks of the crystalline area northwest of the Boston Basin were exposed to erosion at the time of the deposition of the upper conglomerate. The occurrence of granite pebbles eight or ten inches in diameter at Attleboro within the Narragansett Basin, and twenty or thirty miles from present occurrences of muscovite granite, indicates that the

granite area must then have had relatively a much greater elevation than now, in order to give sufficient grade for the transportation of such coarse material so great a distance. Similarly, the presence of equally large pebbles of quartzite at the Attleboro locality, together with the noted increase in the size and abundance of these pebbles southward, indicate that the land in that direction must also have had a considerable relief while the Dighton Conglomerates were forming.

While it is thus seen that the land must have had some diversity of form at the time when the latter part of the Carboniferous record in the Narragansett Basin was being made, some of the lower members of the series indicate that such was not the case throughout the deposition period. The basal arkose with the overlying quartz-pebble conglomerate and finer beds indicate that previous to the deposition of the sediments, and probably also during the early part of that period, the country was without great differences in relief, else the arkosic material would not have formed in sufficient quantity to permit its later accumulation in the present beds.

Question of Original Basins. In his earlier studies Crosby stated vigorously his view that the "Basins probably existed as such before the deposition of the sediments which they contain" (Crosby, b, p. 181). Similar views were advocated by Shaler and Foerste. The former regarded them as "erosion troughs which became the seats of excessive deposition," which "brought about the lowering of the surface in relation to the original bedding" (Shaler et al., p. 13). Shaler, however, differed from Crosby's early view in regarding the ancient erosion troughs as far more extensive than the present basins. He considered the Narragansett Basin as a broad trough penetrating far into the land and possibly including the Worcester trough (ibid., p. 9), while Crosby considered the former basins as practically of the same area as those of the present (b, p. 181). Foerste also adopted the idea of pre-existing basins, for he wrote of the Precarboniferous floor as being "partly above water and furnishing material for arkose and conglomerate" (Shaler et al., p. 376). In his later work Crosby has made radical changes in his ideas on this subject, for in his paper on the Blue Hills Complex he states that it is improbable that the basins of the existing Carboniferous rocks were even outlined before deposition began (n, p. 464).

The argument for the pre-existing basins seems to be based chiefly on analogy but Shaler calls attention to the structure of the Carboniferous rocks of the Narragansett Basin — close folds, somewhat overturned toward the borders, and open symmetrical folds within —

and argues that this arrangement is due to the transmission of thrusts by lateral girders of compact crystalline rocks to the weaker rocks within the basin and that the effects of the thrusts are most marked at the borders because the more yielding sediments are not good transmitters (Shaler et al., p. 21–22). This argument appears to be well taken and seems to apply in the case of the Narragansett Basin but in the Boston Basin the evidence is not so clear. The thickness of the sediments in the latter region is, indeed, not nearly so great as in the Narragansett Basin but even so it would seem that similar phenomena should there be noted, even if in a less degree; but so far as the writer's investigations have gone, there does not seem to be any definite tendency toward more marked metamorphism along the borders than within the basin. On the contrary, some of the best marked examples of deformation occur well within the basin.

If the present sites of the various basins were originally separate erosion troughs or a single great depression, occupied either by rivers or by the sea, before the deposition of Carboniferous rocks began, it seems to the writer that there should be evidence of such conditions in the form of sedimentary deposits between the crystalline floor and the lower members of the Carboniferous series. Such rocks may indeed exist, overlapped by the Carboniferous beds, but so far as the contacts of the latter with the underlying terrane have been described no evidence of their existence has been found. In fact, there appears to be no definite evidence that any sediments were deposited in this region from Middle Cambrian to Carboniferous times. It seems probable, therefore, that both the sites of the basins and the surrounding country were land areas exposed to subaërial conditions prior to the deposition of the Carboniferous rocks. The fact that the conglomerates in all the basins contain so large a proportion of granite pebbles, together with the fact that finer granitic debris is represented in the basal sediments of each basin, lends support to this view; for granite is ordinarily a deep-seated rock and its exposure at the surface at the beginning of Carboniferous deposition is in itself evidence of long continued existence as a land area before Carboniferous times.

If the floors of the basins owe their present form to the orogenic agencies that folded the sediments it would be expected that they would show some effects of the deformation experienced both by themselves and by the overlying strata. Evidences of this character are not entirely lacking, for at certain places along the east side of the Narragansett Basin the marginal granite has been sheared and rendered locally schitose (Shaler et al., p. 122, 273). In the Boston Basin

it has been shown by Crosby that the felsitic floor has shared in the plications suffered by the overlying sediments (see page 202).

Significance of Arkose. According to Daubrée, arkose is produced by the decomposition and disintegration of granite in place. The quartz separates out in small fragments which are angular, entirely irregular in form and without indication of crystal faces. The aspect of the arkoses of Bourgogne, Auvergne, and other regions, partakes of these characteristics. The quartz is angular and is mixed with a variable quantity of feldspar, more or less altered, and of mica. The rock is visibly the result of a simple rehandling of the granitic sands by water, without attrition (Daubrée, p. 255). The arkose at East Dedham, in the Boston Basin, and at Pondville, in the Norfolk Basin, corresponds very well with this description, while that in the Narragansett Basin is more decomposed and less easily recognized.

Regarding the significance of arkose, all seem to agree that such an accumulation means a period in which granitic rocks were disintegrated more rapidly than the loosened material could be removed, followed by a period in which the debris was hastily washed away and deposited. There is, however, some difference of opinion as to the climatic conditions under which the disintegration takes place. Shaler states his view in the following words: "Judging by the conditions which have affected the fields that now afford or that might produce the arkose deposits, we may assume that these levels of the Coal Measures time had long been the seat of a considerable rainfall and had maintained a coating of vegetation, such being the antecedent conditions of any decomposition that would prepare the way for arkoses" (Shaler et al., p. 52). On the other hand, Oldham, discussing the occurrence of undecomposed feldspar in sandstones of the Panchet group of India (one of the members of the Gondwana system), states that the disintegration of the parent rock, from which the materials were derived, went on at a greater rate than the chemical decomposition of the constituent minerals. He thinks that this might be due either to extreme dryness, which would retard the rate of decomposition, or to extreme severity of climate, which would accelerate the rate of disintegration (a, p. 201).

The important feature of the arkose in this connection is the relatively fresh state of the contained feldspar. Under the conditions of considerable rainfall and vegetative covering, postulated by Shaler, it seems probable that the feldspars of the parent rock would undergo comparatively speedy chemical disintegration, for water bearing various mineral and organic solvents would percolate through all the

interstices of the rock. Thus it would appear that the residual products of the disintegration would be quartz grains and clay, shading downward through successively less decomposed material, into the unchanged rock. In this case, however, it is probable that the loosened, undecomposed material below would be relatively coarse and not of sufficiently fine texture to form arkose of the type exposed at Pondville. Should such materials be subjected to rapid transportation and deposition, beds of sandstone, clay, and coarser granitic fragments would undoubtedly be formed, but it is not probable that the feldspars of gritty texture would have escaped some degree of chemical decomposition.

For the production of true arkose it would seem that climatic conditions are needed that are not so favorable for the decay of the feldspars as those suggested by Professor Shaler. The suggestion of Oldham that extreme severity of climate will account for the occurrence of undecomposed feldspars in feldspathic sandstone appears to be borne out by the character of many glacial accumulations; for fragments of fresh feldspar are frequently found in boulder-clay and in fluvio-glacial deposits. Nevertheless, true arkose is not found in glacial deposits. The supposition of extreme dryness, suggested by Oldham as an alternative, might indeed account for the comminution of granitic rocks without chemical decay and for the production of fragments of undecomposed feldspar; but in the deserts of warm temperate or tropical latitudes, where arid conditions are displayed to best advantage, no deposits resembling arkose have been observed. According to Shaler, there are no observations on record of arkose now in the process of formation (Shaler et al., p. 53). The prime requirement seems to be a set of climatic conditions that favor mechanical disintegration without permitting much chemical decay. It has been shown that none of the above mentioned conditions is entirely favorable. Probably the true conditions are intermediate between the extremes noted. A moderately cool and arid climate, such as would obtain at moderately high altitudes in the lee of lofty mountain ranges, or in continental interiors, would more likely be suitable.

Significance of Color. In all three basins red colors are found in some members of the Carboniferous series and in the sediments of the Norfolk and Narragansett Basins they are conspicuous features. The red color furnishes an important clue to the geographical conditions of the time, when the now consolidated strata were still loosened waste, unremoved from its parent ledges. As Shaler remarks, the red color in sediments may be due to several causes: the waste from

rocks originally red, the alteration of lime carbonate to siderite and then to limonite, as in the Devonian and Silurian rocks of the Appalachians, or to the decay of crystalline rocks containing iron (Shaler et al., p. 62). In the case before us there seems to be evidence of the agency of at least the first and last causes. Red strata of earlier date occur in proximity to the Carboniferous deposits, especially in the Narragansett Basin. But probably the decomposition of iron-bearing rocks, abundantly shown by the occurrence of arkose in all three basins, has been the most effective cause. According to Russell, red residual deposits are the product of warm humid regions, while the corresponding deposits of arid regions are not red but light colored, usually gray or yellow brown (a, p. 46).

Precarboniferous Climate. The abundance of the red rocks among the Carboniferous sediments in this region, therefore, seems at first sight to indicate that prior to the deposition of the strata a warm and humid climate, perhaps similar to the tropics of the present day, prevailed in this region, as postulated by Crosby and Bouvé (Crosby, n, p. 463–464). But it has been shown that the arkose deposits, with relatively fresh feldspar, indicate that the moisture could not have been excessive. The climatic conditions could not therefore have been so humid as those of the present tropical regions, nor so dry as the arid tracts of the West. The combination of the arkose deposits with the red sediments must mean former climatic conditions of moderate or scanty rainfall and cool temperature.

Since the great depth of disintegration shown by the character of the basal Carboniferous sediments indicates generally low grades prior to the deposition of the strata, the cool temperature may be ascribed to general climatic conditions and not to altitude; for it is hard to reconcile low grades of streams and deep disintegration of granitic rocks with high altitudes. The scantiness of the rainfall may be ascribed to the presence of mountains or a land mass, separating the region from the ocean on the east, more or less subdued but sufficiently high or extensive to intercept much of the rainfall. The general character of the country in Precarboniferous times may perhaps be fairly compared to that of the present Piedmont plateau of the eastern United States, if the features of cool climate and country to the east were added, as above suggested.

The supposition of cool climate for this latitude at the time the disintegration of the rocks was in progress is not wholly without warrant, for it has been shown on page 130 that actual glacial conditions occurred over an extensive region in the low latitudes of the

eastern hemisphere at a time which may have been coincident with the deposition of at least a part of the Carboniferous series of eastern Massachusetts. The inauguration of these glacial conditions was doubtless gradual, and was probably due to causes sufficiently general to have affected regions remote from the area known to have been glaciated.

The supposition of mountains to the east and southeast has already received some support from the discussion of the sources of material in the conglomerates. That mountain building occurred in New England in Precarboniferous times is indicated by the existing ranges along the western border of Connecticut and the states northward and by the metamorphic rocks of eastern New England that have trends similar to those ranges. Materials from these ancient mountains are included in the Carboniferous conglomerates, for Woodworth has observed cleaved pebbles of quartzite in the conglomerate near North Attleboro, in which the cleavage planes of any given pebble lie in positions entirely unrelated to those of neighboring pebbles or to the present attitude of the inclosing rock (d, p. 181). The broad questions raised by the suggestion of the disappearance of a former mountain range or perhaps a more extensive land mass along what is now the coast of Massachusetts are beyond the scope of this paper; but it may be remarked in this connection that the abrupt breaks in the structure of the lands at the sea coast in many parts of the North Atlantic ocean are highly suggestive of down-faulting. The coasts of Nova Scotia, Labrador, Iceland, and southwest Ireland may be cited as cases in point.

Summary of Geographical Conditions. (1) An attempt to restore the present beds to their previous undeformed condition shows that they would form a mass at least 60 miles long and 30 miles wide, attaining a height above their base of 12,000 feet toward the south but thinning down to 5,000 feet or less northward.

(2) At the time of the deposition of the upper or Dighton Conglomerate in the Narragansett Basin there was probably high land south and east of the Narragansett Basin and northwest of the Boston Basin, but prior to the deposition of the sediments the land now occupied by the several basins was without much diversity of form and of relatively low elevation.

(3) The areas now occupied by sediments were not certainly outlined as basins previous to the deposition of the strata.

(4) The arkose and red beds indicate that the region was subjected to long subaërial decay under conditions of cool climate and moderate or scanty rain fall.

(5) The region was probably bounded on the east and southeast by more or less subdued mountains, or by a land area of sufficient height and extent to deprive passing winds of much of their moisture.

Hypotheses of Origin.— *General Statement.* The principal features that may be expected to appear in the various types of conglomerate are shown in the tabular summary on pages 150–151. In the following paragraphs the characteristics of the sedimentary series in each basin will be given in accordance with the items of the table, together with brief comparisons.

Marine. Perhaps the clearest statement of the marine view of origin is given by Crosby. He claims that the stable marine conditions of Precarboniferous times gave way to an encroachment of the sea upon the land, attended, however, by marked and oft-repeated oscillations of level, which spread sediments far and wide over the entire region (n, p. 461, 464). According to this view the conditions of deposition were like those under which the Cretaceous rocks of Texas were formed, as described by Hill. A comparison of the features of the Carboniferous sediments of eastern Massachusetts with the features of marine deposits as indicated in the table shows some points of agreement, together with many differences.

The matrices of the various conglomerates under consideration can scarcely be described as composed of clean sands. They ordinarily contain much felsitic material and some feldspar and are composed of grains not well sorted, but generally of variable size and with little appearance of arrangement. The grains are usually angular or subangular and but seldom rounded.

The pebbles, with the exceptions already stated (page 164), are of local materials. They are variable in shape and size and are on the whole subangular rather than well rounded. No markings other than pressure striations and indentations have been observed upon them.

The colors of the Roxbury series are usually grayish, with reddish, purplish, or greenish tones, but the red colors are only locally intense. In the Norfolk and Narragansett Basins, however, extensive areas of deeply red colored sediments occur.

Stratification is not well shown in the coarser conglomerates but is fairly well indicated where finer sediments appear. Cross-bedding is seen in all three areas but it is not of frequent occurrence. In the Boston and Norfolk Basins, so far as known, the coarsest sediments are at the base of the series and are overlaid by strata, which, with

various alternations, become successively finer. In this respect the sedimentary series of these two basins appear to conform to the arrangement observed in the case of the transgressing sea, as described by Hill. In the Narragansett Basin, however, this condition does not obtain. There the coarsest conglomerates occur at the top of the series. Local unconformities have been observed only in the Narragansett Basin but evidences of contemporaneous erosion occur in all three basins. Lenses occur in the sediments of each basin but their relations as regards original dip and strike are not clear. They seem, however, to be distributed along the same horizon or in parallel horizons. Limestones do not occur in the Roxbury series but in both the Norfolk and Narragansett Basins isolated outcrops of minor importance have been found. In these cases, however, the limestone is not fossiliferous but is nodular and concretionary and evidently of secondary origin.

The strata in all three basins have been found to rest upon surfaces long subjected to subaerial decay.

Lacustrine. The matrices of the Carboniferous conglomerates, as described above, agree perhaps more closely with the lacustrine type than with the marine; for in the lacustrine type the sands are less clean, and less well sorted and rounded than is the case with marine sediments. Nevertheless, the lack of uniformity in composition and size of the grains is more marked than is suggested by the descriptive terms used in the table relative to lacustrine deposits.

In the case of the pebbles, too, a similar comparison may be made.

There is nothing distinctive about the color of lacustrine deposits. Russell states that lacustrine sediments are usually not red but that, should lake basins occur in regions of deep disintegration, like the southern Appalachians, the sediments deposited in such lakes would be red (a, p. 47–48). The Carboniferous sediments of eastern Massachusetts were formed in a region where there had been deep subaërial decay, so that if lacustrine sediments were deposited they would naturally have more or less red color. It has been shown that red colors are developed in the strata of each basin.

The stratification of lacustrine deposits may be expected to resemble that of marine beds, except that the respective features would perhaps be less well developed. The stratification of the sediments under discussion is not well defined except in the finer textured members, but there the tendency is toward the production of more or less definite bands, rather than of lenses. In the Boston and Norfolk Basins the succession of the sediments seems to be from coarse, toward

the base, to fine above, in accordance with the idea of marine transgression; but in the Narragansett Basin the coarsest sediments overlie rocks of finer texture, in conformity with the normal cycle of fresh-water deposition. The few instances of limestone deposits show no sign of organisms, either fresh water or marine.

Estuarine. Perhaps the most abundant and distinctive component of estuarine deposits is fine mud. Argillaceous materials are represented to some extent in the matrices of the various conglomerates; they are not particularly abundant. In certain places, however, the matrix of the conglomerate appears to be felsitic, and it may be that before consolidation this material was a felsitic mud. Fine gravel and sand are certainly represented in the conglomerates of the three basins and the grains of the matrices are usually angular, subangular, and ill sorted, but they are not ordinarily cross-stratified.

The pebbles of the various conglomerates might agree well enough with the expected characteristics of estuarine conglomerates. They are of local materials, with the exceptions noted, of variable size, and not well rounded nor sorted.

So far as color is concerned, the conglomerates in question would meet the expectation of estuarine conglomerates, for red colors occur in each basin.

Frequent and irregular bedding of coarse sands and finer materials may be said to occur in some measure among the finer sediments of the several series, but it cannot be said to be so marked a characteristic as is implied in the table. Cross-stratification, which should occur frequently in estuarine deposits, is only an occasional feature of the rocks under consideration. Ripple-marked surfaces, with sun-cracks and other markings, which should appear frequently in estuarine sediments, are of relatively uncommon occurrence in the Carboniferous rocks of the several basins.

Fluviatile. With the exception of cross-stratification, the features of the matrices of the several conglomerates agree well with the expected features of fluviatile conglomerate; for they consist of sands mingled with finer and coarser material, in angular to subangular grains, not well sorted.

The pebbles, too, conform with the description of fluviatile deposits. At any outcrop of conglomerate the pebbles usually present a wide variation in size, sometimes, as at Squantum, Hingham, and Purgatory, exceeding one or two feet in diameter. In general the pebbles of the conglomerates of the several basins are subangular but they present all shapes from angular to rounded. Moreover, fragments

of one stratum occur as pebbles in another stratum in a number of widely separated localities. None of the pebbles, however, display markings other than the pressure striations and indentations mentioned above.

In color the sediments of the three basins would meet the expectation suggested by the table.

Frequent alternations of coarse and fine beds occur in all the basins, especially in the vicinity of the finer sediments. Current markings and oblique lamination do occur, but they are relatively infrequent. Well-marked local unconformities have been observed in the Narragansett Basin near Attleboro, and in the other basins evidences of such conditions are furnished by the pebbles of contemporaneous sandstone, grit, and conglomerate found in the conglomerates at several localities. The limestone found in the Norfolk and Narragansett Basins consist of amorphous carbonate of lime and is not of organic origin.

Crush. The Carboniferous sediments of the three basins present little resemblance to crush-conglomerates, according to the characteristics of the latter outlined in the table. The subangular shapes of the pebbles and the occurrence of fracture planes and tension cracks in some of the pebbles are the only similarities observed.

Glacial. Nothing definitely comparable to glacial boulder-clay has been observed in the conglomerates of any of the basins. The grains of the matrix are both coarse and fine and generally angular or subangular. No cases have been observed where the same grain appears partly angular and partly rounded. Broken grains of feldspar are often present in the matrix but they usually show some sign of alteration. Occasionally, however, they are relatively fresh. The matrix cannot be said to be as compact as in the specimen of the Dwyka Conglomerate studied by the writer.

The pebbles are generally of local material but it has been observed that in the case of two varieties the source may have been remote. Generally there is little assortment either of size or kind. At Squantum and at Huit's Cove in Hingham boulders several feet in diameter occur among smaller fragments in heterogeneous arrangement, but these are exceptional and very local occurrences. The larger boulders at these localities do not appear to have come from a remote source but are of rocks similar to those now occurring along the margin of the basin. The pebbles of the various conglomerates do not show the characteristic traits of glacial pebbles and do not bear any glacial markings.

The colors of some parts of the conglomerate series would corre-

spond well enough with those indicated as characteristic of glacial deposits; for in many places the rocks are dark gray with greenish tints and sometimes with bluish tints. The very noticeable red colors of other portions of the series do not, however, agree with the ordinary colors of glacial deposits.

The conglomerates of all the basins have been shown to exhibit some degree of bedding, but the latter is often poorly defined. Occasional pockets and lenses of coarser and finer material, with cross-bedding, occur in the less well stratified masses. In this respect they seem to resemble both fluviatile and glacial deposits. There is no case where large boulders have been observed in the midst of fine and evenly bedded deposits, but there are localities where pebbles a foot or more in diameter are scattered through finer conglomerate or grit that is poorly bedded.

The conglomerates have nowhere been observed to lie upon glaciated surfaces. In all cases where the basal contacts have been observed, the underlying rock has shown evidence of subaërial decay.

General Discussion. — *General Statement.* In the foregoing comparison of the Carboniferous conglomerates of this region with the characteristics of the various types as outlined in the table it has been shown that the former have some resemblance to each of the given types, and that there is no case where the correspondence is complete. Probably, then, the conglomerates have been formed by the combined action of two or more of the given processes. It now remains to consider the above comparisons in connection with other general data and to discuss the relative merits of the several hypotheses of origin.

Marine. The writer has seen no clear statement of the argument for the marine origin of the conglomerate. Such origin seems to have been assumed from the general water-worn condition of the pebbles in the conglomerate and from the present proximity of the sea. In an argument against the suggestion of glacial origin, Crosby cites the following facts in favor of the marine idea: (b, p. 187): —

(1) the lithologic passage from conglomerate to slate.

(2) the undoubted conformability of the slate and the conglomerate.

(3) the evident stratification of the conglomerate.

(4) the absence of striated pebbles.

(5) the local origin of the materials.

(6) the evidence of sorting by water.

No other aqueous agency than the sea appears to have been considered but it will be observed by reference to the table, pages 150–151, that the features indicated by Crosby are not confined to marine conglomerates. The main arguments in favor of marine origin seem to be:—

(1) the apparent gradation upward from coarse to fine texture in the Boston Basin and in the northeast part of the Norfolk Basin;

(2) the prevalence of banding as the type of bedding, indicating a tendency to regularity rather than to irregularity of stratification;

(3) the distribution of lenses, so far as observed, in the same horizon or in parallel horizons, showing a similar tendency.

The argument of gradation upwards in texture from coarse to fine does not hold for the Narragansett Basin and the southwest part of the Norfolk Basin, for in the former case the coarsest conglomerates lie at the top of the series and in the latter case arkoses and finer sediments lie at the base, while coarse conglomerates of uncertain stratigraphic position occur apparently higher in the series. Moreover, it is not certain that the upper part of the Carboniferous series is seen in the Boston Basin. If the crystallines of the northwest highlands are the source of the muscovitic material of the Narragansett Basin, the absence of such material from the Boston Basin must mean that the muscovitic rocks to the northwest were not exposed to erosion at the time the present sediments of the Boston Basin were forming, and that the latter rocks are not the equivalents of the upper members of the Narragansett Basin series, but are stratigraphically below them. In that case the upper members of the Roxbury series have probably been removed by erosion and they may have been coarse in texture like the upper strata of the Narragansett Basin. The arrangement observed in the Narragansett Basin is the normal order in fresh-water deposits but unlike the usual succession of marine strata.

If the deposits of the entire region were the result of the encroachment of the sea upon the land it is difficult to account for the presence of such large pebbles of muscovite granite and quartzite, as appear in the Dighton Conglomerate at Attleboro, so far from their apparent sources. Pebbles eight inches or a foot or more in diameter could not have been dragged twenty or thirty miles by marine waves and currents. Some other agents, such as rivers or glaciers, must have transported the material from its sources and delivered it to the sea, if it were the latter that really resorted the debris. But the lithological study of the rocks of the several basins has shown that the component materials are less well rounded and assorted, and less

evenly bedded than is usually the case with marine sediments, and that contemporaneous erosion has occurred in all three basins. Moreover, the fossils that have been found in the Norfolk and Narragansett Basins are more closely allied to fresh-water than to marine types. Thus it appears that in the Narragansett and Norfolk Basins, at least, the sea was not the agent that finally deposited the sediments. In the Boston Basin the lithological similarity of the Roxbury Conglomerate to the Norfolk and Narragansett Basin Conglomerates, together with the resemblance of the obscure fossils discovered by Burr to certain plant remains discovered by Crosby and Barton in the Norfolk Basin, favor a like conclusion. On the other hand, the Somerville and Neponset slates are unlike the slates and shales of the Narragansett Basin. The latter are often micaceous, carbonaceous, and fossiliferous and more or less intermingled with sand. The Somerville and Neponset slates, on the other hand, are more uniform in texture, not micaceous and not certainly fossiliferous, though obscure traces of fossils have been found that tend to ally the slates more with marine than with fresh-water conditions. As stated previously, these differences form the main basis of the argument for the Cambrian age of these slates. Assuming them to be Carboniferous, however, as their structure seems to indicate, it seems hardly possible to consider them marine in view of the probable fresh-water origin of the great mass of sediments in the three basins, with which they appear to be intimately associated.

Lacustrine. The idea of the existence of lakes during the deposition of the Carboniferous sediments of the Narragansett Basin is suggested by both Shaler and Woodworth (Shaler et al., p. 53, 177). The comparisons on pages 248 and 249 have shown that the texture, character, and bedding of the several members of the series in the three basins more closely resemble the characteristics of lacustrine sediments than of marine deposits; for, while a certain degree of uniformity and regularity in composition and stratification is attained by the Carboniferous deposits, these features are not so well developed as might be expected in the case of marine strata. The apparent gradation in texture in the sediments of the Boston Basin tends to favor the marine idea but it has been shown that upper and perhaps coarser members of the series have probably been eroded away. The evidences of fresh-water origin cited in the previous paragraphs favor the hypothesis of lacustrine origin for at least the more uniformly arranged portions of the sediments. On the other hand, the coarseness of the conglomerate and the irregularities of texture and bedding of certain parts

of the series, such as the phenomena observed at Squantum, Huit's Cove in Hingham, Attleboro, and Purgatory, indicate that lacustrine action was not alone responsible for the deposition of the Carboniferous series but that powerful agents of transportation were at work supplying and perhaps depositing some of the detritus.

Estuarine. The idea of estuarine origin was held by Crosby in connection with his earlier views of the marine origin of the conglomerate (b, p. 252). Other writers have described the early condition of the region as a "broad erosion trough" or an "arm of the sea" (Shaler et al., p. 9; LaForge, p. 90), expressions which might be interpreted as implying estuarine origin. In the comparisons on page 249 it was shown that while there were a number of points of resemblance between the characteristics of the sediments of the several basins and the features that may be expected in estuarine strata, yet the agreement in texture and in features of bedding was not so close as in the case of some of the other types. Moreover, the absence of any definite traces of marine life and of brackish water forms, unless some of the plant remains can be so considered, is opposed to the idea of estuarine conditions. The red colors, ripple-marks, mud-cracks and organic impressions that have been observed at various localities are not so frequent as might be expected in strata of estuarine origin; and they are not distinctive, since such features may be expected to occur in fluviatile sediments.

Fluviatile. The fluviatile origin of some of the sediments of the Narragansett Basin has been advocated by Shaler and Woodworth (Shaler et al., p. 53, 67, 176). From the comparisons on pages 249 and 250 it will be seen that the characteristics of the sediments under discussion agree perhaps more closely with the features of fluviatile deposits than with those of any other type, although even here the correspondence is not complete. The bedding is on the whole more regular than might be expected in fluviatile strata and the arrangement of lenses, so far as observed, does not appear to agree with the idea of linear bundles. Nevertheless, it has been shown that fluviatile deposits present a wide range in texture and bedding, from high irregularity to almost complete regularity. Thus the prevalence of banding and fairly uniform bedding need not preclude the idea of fluviatile origin. The evidences of fresh-water deposition already mentioned are favorable to this view and the occurrence of the coarsest conglomerate at the top of the Narragansett series, previously advanced in support of the non-marine character of the sediments, is also favorable; for Oldham has pointed out (see page 112) that in the fluviatile

deposits of India coarser sediments tend to encroach upon and to overlie the finer materials near the mountains.

It may be questioned whether fluviatile agencies are able to accumulate so great a thickness of sediments as that known to occur in the Narragansett Basin, and especially so great a bulk of fine silts and sands as that indicated by the Somerville and Cambridge slates. In reply the case of the Siwalik group of India noted on page 111 may be cited. This group, assigned to fluviatile origin, attains a thickness in the northwest Punjab estimated at 14,000 feet. As regards the second phase of the question it has been shown (page 112) that the boring at Lucknow, in the Indo-Gangetic plain, passed through 1,336 feet of alluvial deposits consisting chiefly of more or less sandy clays. A still more remarkable case (see page 118) is found in the Great Valley of California, where, according to Ransome, borings in the San Joaquin valley at Stockton have penetrated 2,000 and 3,000 feet respectively in unconsolidated fluviatile deposits consisting chiefly of fine sands and clays. Professor Davis, speaking of the aggraded plains of Turkestan, says, "Certainly no one who sees the river-made area of the plains of Turkestan can doubt the capacity of rivers to lay down extensive fine-textured deposits" (Davis, p. 55).

Crush. The general lack of similarity of the rocks of the three basins to crush conglomerates, as shown by the comparisons on page 250, render any further consideration of this mode of origin unnecessary.

Glacial. Professor Shaler has been the most earnest supporter of the glacial hypothesis (Shaler et al., p. 64–67), though Dodge (page 103) also recognized the possibility of such origin. From the comparisons on pages 250 and 251 it appears that no deposits definitely comparable to boulder-clay have been observed among the deposits of the several basins and that no definitely faceted pebbles or pebbles bearing striae have been found. Furthermore, the conglomerates and accompanying sediments do not lie upon glaciated surfaces, but instead they rest upon a surface long subjected to subaërial decay. These facts show that glaciers could not have been the direct agents by which the Carboniferous sediments of this region were deposited.

Indirect glacial action, however, is not precluded. Indeed, there are a number of reasons for believing that glaciers were active agents in preparing the material for deposition. The tumultuous arrangement of pebbles, not faceted nor striated, but more or less water worn, observed at some localities, might be explicable as merely a result of fluviatile action, but it is eminently characteristic of fluvio-glacial

material. The great quantity of relatively large pebbles in the conglomerate indicates vigorous erosion and rapid deposition. The steep gradients required for the transportation of such materials, sometimes for great distances, as in the case of the muscovite granite at Attleboro, indicate that the material was derived from sources at sufficient elevation to warrant the supposition of the existence of at least Alpine glaciers. The occurrence of the Obolus pebbles in the conglomerate of the Narragansett Basin lends support to the view that some material may have been imported by glaciers from outside sources, but it has been shown (page 169) that these pebbles may have been derived from a neighboring land mass not now extant. Perhaps the strongest argument for the agency of glaciers is found in the relative freshness of the granitic pebbles of the conglomerate and in the feldspathic character of the matrix. The feldspar fragments certainly often show signs of alteration, but when deposited they must have been practically fresh. The accumulation of so much coarse and fresh material means harsh erosion in certain areas and rapid deposition in adjoining regions. Such conditions are eminently characteristic of regions now subject to glaciation. The actual evidence of glaciation in the areas that furnished the debris might easily have been effaced by subsequent erosion; but the character of much of the remaining deposit is similar to that which might be laid by torrents overburdened by coarse glacial waste upon emergence from their mountain gorges.

Conclusions as to Origin.—The evidence adduced in the preceding paragraphs is largely negative and unsatisfactory. The bedding and texture of the sediments, though attaining a fair degree of regularity, do not display these features in so high a degree of development as might be expected in true marine strata. The apparent gradation upward from coarse to fine texture in the Boston Basin, suggestive of marine transgression, is offset by the occurrence in the Narragansett Basin of a gradation in the opposite direction, suggestive of non-marine deposition. The fossils thus far found in the Narragansett and Norfolk Basins are indicative of non-marine rather than of marine origin. Similar evidence is borne by the irregularities of bedding and of texture. The lithological similarity of the Roxbury Conglomerate to the rocks of the Norfolk and Narragansett Basins makes it probable that all are of like origin and that the entire Carboniferous series of this region is non-marine. More than one process, however, was concerned in the formation

of the series. The more regular and even bedded portions are suggestive of quiet fluviatile or lacustrine origin, while the more irregular and tumultuous portions of the deposit indicate torrent action. The great quantity of large pebbles of relatively fresh granite and the abundance of feldspathic material in the sandstones and in the matrices of the conglomerates suggest that much material was furnished to the streams of that time by glaciers of which no direct evidence now exists.

The Harvard Conglomerate.— On the supposition that the Harvard Conglomerate is Carboniferous it is likely that its history may be linked with that of the Carboniferous sediments farther east. In spite of the deformation that it has experienced, the form and arrangement of some of the pebbles seem to indicate that it was originally poorly assorted and that its pebbles were irregular in shape, features that tend to ally it more closely with non-marine than with marine sediments. The fact that its main constituent is a peculiar form of quartzite, unlike any of the known quartzites of the region, makes its origin a matter of considerable doubt. If the quartzite is an aeolian formation, as suggested by Emerson (see page 169), it might have been formed during some halt in the process of deposition and later have been rapidly eroded and deposited. The general fine texture of the great body of sediments westward, with which it seems to be most intimately connected, indicates that the region now occupied by them was more remote from the sources of supply than was the case with the sediments of eastern Massachusetts. Thus if any connection may be supposed to have existed between the strata in the vicinity of Harvard and Worcester and those of the Narragansett and other basins farther east, it may perhaps have been such as regions in the Indo-Gangetic plain of today bear to the Bhábar regions along the sides of the mountains. It must be admitted, however, that the relations postulated are highly conjectural.

Conditions of Deposition.— The character of the basal sediments of the three basins and of the underlying floor indicate that at the beginning of the period of deposition the area now occupied by the present strata, together with a considerable district of the surrounding country, must have had a more or less subdued topography with relatively low grades. The area does not appear to have been a great valley, as suggested by Shaler (see page 241), for no sediments immediately antedating the Carboniferous occur between the latter and the subjacent crystallines, though it is

possible that such may have existed and have been removed by the same erosion that stripped the disintegrated material from the surrounding country in the early part of the deposition period. It is, however, fairly certain that, during the latter part of that period, mountains existed to the northwest of the Boston Basin, as shown by the muscovitic material in the Dighton Conglomerate, and these may have been represented in subdued form before the deposition of the Carboniferous strata began. The combination of arkose and of red strata in the lower part of the series indicates that the climate must have been cool and the rainfall moderate or scanty. Thus a mountain region of moderate elevation or a land area of greater or less extent must have intervened between the region now occupied by the Carboniferous strata and the sea.

The deposition of the sediments was inaugurated by changes that permitted rapid removal and deposition of the decayed material, then covering the entire region, and the vigorous attack on the fresh subjacent rock. These changes may have been partly climatic but probably they were chiefly orogenic; for at the close of the deposition period, as recorded in the Narragansett Basin, land areas must have existed both to the northwest and the southeast, sufficiently high to have furnished the grades necessary for the transportation of such coarse material as is found in the Dighton and Purgatory Conglomerates. Doubtless these elevations were of sufficient altitude to support active glaciers. There are many indirect evidences that such was the case.

The orogenic movement may have been simply differential uplift, whereby certain areas became subject to vigorous erosion, while other regions received extensive deposits, or it may have been such an uplift accompanied by faulting. The evidence of probable boundary faults in the Boston and Norfolk Basins and the occurrence of contemporaneous igneous activity, so marked in the Boston and Narragansett Basins, tend to show that block faulting may have occurred during the deposition of the sediments and may perhaps have been responsible for the relief that permitted such vigorous erosion. The somewhat uncertain evidence furnished by the coarse conglomerate along the south base of the Blue Hill Range is favorable to this view. At least two systems of block faults can be recognized throughout the region, having respectively north-south and east-west trends. The north-south faults of Pondville are seen to be younger than the folding of the sediments, therefore younger than the period of deposition; but no evidence is known to the writer that proves the east-west faults

to be younger than the folding. The overthrust fault at Chestnut Hill Reservoir belongs to a different type and probably accompanied the folding. The east-west block faults may, however, have accompanied the deposition of the strata.

According to this view the deposition of the sediments, begun during a broad differential uplift of the region, may have become more or less localized in orogenic basins developed by block faulting during later deposition. The main blocks thus formed, so far as this region was concerned, were perhaps the northwest highland region and the supposed upland to the southeast, now no longer extant. Between lay, perhaps, several minor blocks, one of which, upthrown, may now be represented by the Blue Hill Range. As deposition progressed, doubtless the minor blocks may have been buried by the accumulating sediment from the higher lands; but there is no definite evidence that at any time the respective basins were without outlets.

How extensive the region thus affected may have been there is no means of knowing. The occurrence of the conglomerate areas at Bellingham, Woonsocket, and Harvard and in the basin of the Parker river suggests that the conglomerate may formerly have widely exceeded its present limits. Faults of the block type occur frequently in the crystalline rocks of the region, especially in the northwest highlands; but in rocks of such similar character the amount of displacement is not easily estimated. The crystalline floor upon which the sediments may have been deposited has been carried above the plane of erosion and the overlying strata have been worn away.

General Summary.—(1) The estimated bulk of sediments now remaining in the three basins, assuming the dimensions given and an average thickness equal to half the maximum figures, is approximately 1,700 cubic miles.

(2) An attempt to restore the present beds to their previous undeformed condition shows that they would form a mass at least 60 miles long and 30 miles wide, attaining a height above their base of 12,000 feet toward the south but thinning down to 5,000 feet or less northward.

(3) Prior to the deposition of the strata the present basins were not certainly outlined.

(4) The arkose and red beds indicate that the region was subjected to long subaërial decay in Precarboniferous time under conditions of cool climate and moderate or scanty rainfall.

(5) The region at that time was probably bounded on the east and

southeast by more or less subdued mountains, or by a land area of sufficient height and extent to deprive passing winds of much of their moisture.

(6) At the close of the sedimentation period, as registered in the Narragansett Basin, high grades and mountainous conditions prevailed in the regions surrounding the sites of the present basins.

(7) Comparison of the characteristics of the Carboniferous series with the criteria previously obtained from other conglomerates show that several sets of processes combined to form the strata under discussion.

(8) The evidence, largely negative and unsatisfactory, favors non-marine origin.

(9) Glaciers were not directly concerned with the deposition of the conglomerates, but they probably furnished material to torrents, by which it was deposited either upon the land or in lakes.

(10) The conditions of deposition are uncertain but there is some evidence that sedimentation began during a broad differential uplift of the region and was later more or less localized in orogenic basins developed by block faulting during deposition. The basins so formed always maintained outlets.

(11) The extent of the postulated conditions is not certainly known but the evidence of the conglomerates at other localities goes to show that it greatly exceeded the present limits of the basins.

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EXPLANATION OF PLATES.

PLATE 1. Shapes of pebbles in the conglomerate: A, angular; B, subangular; C, rounded; D, rounded, with some well rounded.

PLATE 2. Conglomerate ledge, North Beacon St., Brighton, showing lenticular (A) and rounded (B) types of the so-called slate pebbles.

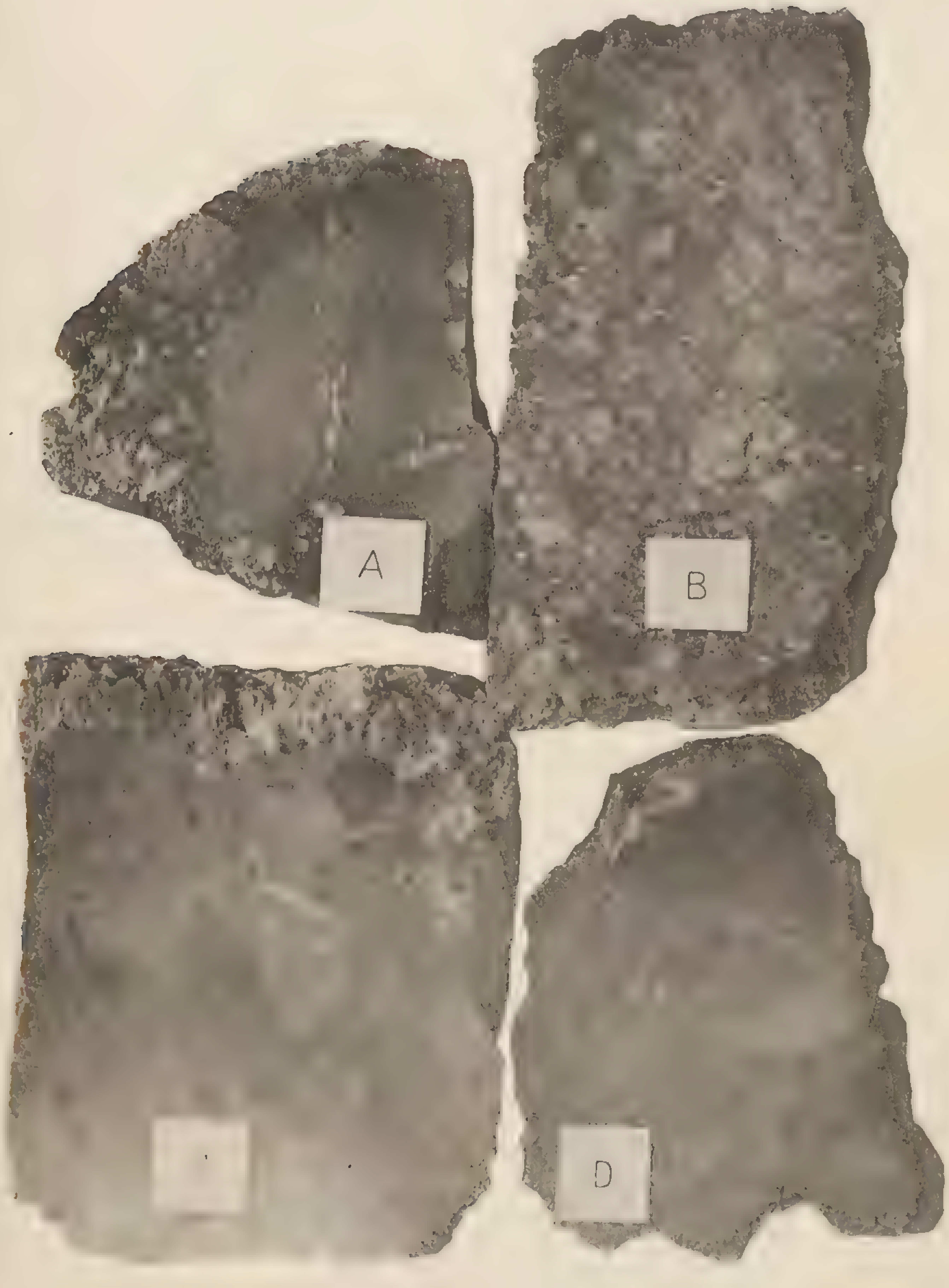
PLATE 3. A. Conglomerate at Squantum showing a large granitic boulder embedded among smaller pebbles. B. Deformed pebbles in the conglomerate at Purgatory near Newport, R. I. The hammer handle is 18 inches long.

PLATE 4. East (A) and south (B) sides of a ledge a few hundred yards northeast of the sharp bend in Commonwealth Ave., Brighton, showing (A) melaphyr cutting across the bedding of sandstone in irregular vertical contact and (B) an irregular strip of sandstone included in the melaphyr.

PLATE 5. Deformed conglomerate at Fogland Point, R. I., showing (A) the bedding of the rock and the stretching of the pebbles; (B) flattened, sliced, indented and striated pebbles. The hammer handle is 18 inches long.

PLATE 6. Geological section southeastward from the asylum grounds at Belmont

PLATE 7. Topographical and geological map.



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GEOLOGICAL SECTION SOUTHEAST FROM THE ASYLUM GROUNDS, BELMONT.

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Bulletin of the Museum of Comparative Zoölogy
AT HARVARD COLLEGE.
Vol. XLIX.

GEOLOGICAL SERIES, Vol. VIII, No. 5.

AN OCCURRENCE OF HARNEY GRANITE IN THE NORTHERN BLACK HILLS.

By Henry G. Ferguson and Fremont N. Turgeon.

With Three Plates.

CAMBRIDGE, MASS., U. S. A.:
PRINTED FOR THE MUSEUM.
February, 1908.

Reports on the Scientific Results of the Expedition to the Eastern Tropical Pacific, in charge of Alexander Agassiz, by the U. S. Fish Commission Steamer "Albatross," from October, 1904, to March, 1905, Lieutenant Commander L. M. Garrett, U. S. N., Commanding, published or in preparation: —

A. AGASSIZ. V.[5] General Report on the Expedition.
A. AGASSIZ. I.[1] Three Letters to Geo. M. Bowers, U. S. Fish Com.
A. AGASSIZ and H. L. CLARK. The Echini.
F. E. BEDDARD. The Earthworms.
H. B. BIGELOW. The Medusae.
R. P. BIGELOW. The Stomatopods.
S. F. CLARKE. VIII.[8] The Hydroids.
W. R. COE. The Nemerteans.
L. J. COLE. The Pycnogonida.
W. H. DALL. The Mollusks.
C. R. EASTMAN. VII.[7] The Sharks' Teeth.
B. W. EVERMANN. The Fishes.
W. G. FARLOW. The Algae.
S. GARMAN. The Reptiles.
H. J. HANSEN. The Cirripeds.
H. J. HANSEN. The Schizopods.
S. HENSHAW. The Insects.
W. E. HOYLE. The Cephalopods.
C. A. KOFOID. III.[3] IX.[9] The Protozoa.
P. KRUMBACH. The Sagittae.
R. VON LENDENFELD and F. URBAN. The Siliceous Sponges.
H. LUDWIG. The Holothurians.
H. LUDWIG. The Starfishes.
H. LUDWIG. The Ophiurans.
—— The Actinaria.
G. W. MÜLLER. The Ostracods.
JOHN MURRAY. The Bottom Specimens.
MARY J. RATHBUN. X.[10] The Crustacea Decapoda.
HARRIET RICHARDSON. II.[2] The Isopods.
W. E. RITTER. IV.[4] The Tunicates.
ALICE ROBERTSON. The Bryozoa.
B. L. ROBINSON. The Plants.
G. O. SARS. The Copepods
F. E. SCHULZE. The Xenophyophoras. XI.[11]
H. R. SIMROTH. The Pteropods and Heteropods.
TH. STUDER. The Alcyonaria.
T. W. VAUGHAN. VI.[6] The Corals.
R. WOLTERECK. The Amphipods.
W. McM. WOODWORTH. The Annelids.

[1] Bull. M. C. Z., Vol. XLVI., No. 4, April, 1905, 22 pp.
[2] Bull. M. C. Z., Vol. XLVI., No. 6, July, 1905, 4 pp., 1 pl.
[3] Bull. M. C. Z., Vol. XLVI., No. 9, September, 1905, 5 pp., 1 pl.
[4] Bull. M. C. Z., Vol. XLVI., No. 13, January, 1906, 22 pp., 3 pls.
[5] Mem. M. C. Z., Vol. XXXIII., January, 1906, 90 pp., 96 pls.
[6] Bull. M. C. Z., Vol. L., No. 3, August, 1906, 14 pp., 10 pls.
[7] Bull. M. C. Z., Vol. L., No. 4, November, 1906, 26 pp., 4 pls.
[8] Mem. M. C. Z., Vol. XXXV., No. 1, February, 1907, 20 pp., 15 pls.
[9] Bull. M. C. Z., Vol. L., No. 6, February, 1907, 48 pp., 18 pls.
[10] Mem. M. C. Z., Vol. XXXV., No. 2, August, 1907, 56 pp., 9 pls.
[11] Bull. M. C. Z., Vol. LI., No. 6, November, 1907, 22 pp., 1 pl.

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With Three Plates.

CAMBRIDGE, MASS., U. S. A.:
PRINTED FOR THE MUSEUM.
February, 1908.

No. 5.— *An Occurrence of Harney Granite in the Northern Black Hills.*

By Henry G. Ferguson and Fremont N. Turgeon.

The centre of the Black Hills dome, in South Dakota, is composed of granite and schists, the former a pegmatitic type occurring chiefly in the Harney Peak region in the southern part of the hills. From this core the Palaeozoic sediments dip away on all sides.

The earlier idea of Black Hills geology was that uplift was due to intrusion of the granite, (Newton, Crosby) but it has since been shown that the granite, like the schists into which it is intruded, is Algonkian and that the uplift took place at the close of the Laramie (Carpenter, Irving, a., b., Jaggar, Darton, a., b., c., Van Hise). In the northern part of the Hills is a large area where intrusive (Eocene) porphyry, contemporaneous with the uplift, forms dikes in the nearly vertical schists, and sills and laccoliths in the gently sloping sediments. That the later intrusions occur only in the northern hills may be due to the better cementing of the southern Algonkian by the earlier granite and its accompanying mineralizers. Such pegmatitic granite has not hitherto been described from the Deadwood district.

While members of the Harvard Summer School in 1904, the writers had the opportunity of studying, under the direction of Dr. Jaggar, a small laccolith in the northern Black Hills, about two miles northeast of Deadwood, S. D. During our study of this district two features of especial interest were noted, namely, the occurrence of Algonkian schist and granite under the domed up Cambrian and the presence of numerous bodies of porphyry to the north and northeast of Whitewood Peak, as shown in Plate 1.

The laccolith has been described by Jaggar (p. 217) as follows:—

"In Whitewood Canyon immediately west of Whitewood Mountain is shown a small laccolithic mass of rhyolite which in cross section resembles Black Butte in the Judith Mountains, described by Weed and Pirsson. The orifice of intrusion appears to have been a fault with upthrow on the north, and a second fault of similar character appears 1 mile farther south, up the canyon. These faults die out within a short distance of the porphyries east and west, and thus appear to be genetically associated with the deformation occasioned by intrusion. The laccolith is quite unsymmetrical, the Silurian and

Carboniferous limestones on the southern side showing no marked deformation except a sharp backward bend at the porphyry contact, while on the northern side the whole Paleozoic series from the lower beds of the Cambrian to the Upper Carboniferous inclusive are upturned at a high angle, overlie the porphyry, and are locally faulted." * * *

"Topographically, Whitewood Canyon laccolith is inconspicuous. The traveller on the Fremont Railroad in Whitewood Canyon below Deadwood would not suspect its presence. In going down the canyon the most striking features seen are the brown Cambrian and white limestone cliffs that rise vertically 600 to 700 feet above the bed of the muddy torrent. At the bridge the line of the railway crosses the southern fault, marked in the cliffs by an abrupt transition from limestone on the south to steep walls of brown Cambrian flags, limestone breccias, and shales, which at the fault are indurated to a gray and black horny rock of chalcedonic aspect. Three-quarters of a mile below, a gulch is seen on the east side of the canyon that has been eroded out on the fault or conduit side of the laccolith. Curious revetting scarps of porphyry that at first sight resemble sediments curve up over the spur on the north side of the small gulch, while on the south side porphyry forms the lower portion of the slope, and above it the contact with dragged limestones forms a small bench. The summit of the porphyry hill on the north side is Cambrian Obolus sandstone, containing a small sill, that outcrops in a ring about the crest. More conspicuous than this summit are the monoclinal ridges of Paleozoic limestone north and northeast, the second being Whitewood Peak [Plate 2, fig. 1 this Bulletin]; at one place the broad yellow bench of Ordovician spotted limestone shows a bare rock face with small faults displacing the beds. This escarpment is a conspicuous landmark from the summits about, and may be seen dipping off the eruptive from the bend of Whitewood Creek, where, at a sharp elbow of stream capture, the railway leaves the canyon by a tunnel through the Minnelusa ridge. [Plate 2, fig. 2, this Bulletin.] The Whitewood Canyon laccolith differs from the Judith Mountains type of unsymmetrical laccolith mountain, Black Butte, in that erosion, by monoclinal shifting, has not progressed far enough to give the porphyry relief above the limestones which encompass it." * * *

"Crook Mountain, adjacent to Whitewood laccolith on the north-[east] and separated from it by the synclinal valley of Sandy Creek, is the type of a laccolithic dome in which as yet the porphyry core has not been revealed by erosion."

The Algonkian.— On the north side of the upper part of the gulch referred to in the passage just quoted, (this gulch is three quarters of a mile below the railroad bridge on Whitewood Creek, east side), occurs an outcrop of Algonkian schist and granite. This outcrop lies two-thirds of a mile S. W. of Whitewood Peak (Plate 1). It is about 70 feet in thickness and consists of schist with two small granite sills. It rests directly on the porphyry and, although the upper contact cannot be seen, it is to all appearances overlain unconformably by the Cambrian. The lamination of this schist dips about 20° S 70° E.

The schist as seen in the hand specimen is a dark green, brilliantly glistening fibrous rock composed of amphibole (actinolite ?) and quartz. It has a banded structure, small light colored quartz bands, about $\frac{1}{8}$ inch across, alternating with the broader dark bands. None of the metamorphic rocks of the Algonkian in the vicinity of Deadwood and Lead, as described by Irving (a., b.) and Van Hise, appear to resemble this schist.

The granite is of greater interest as this appears to be the only outcrop in the Deadwood region and moreover suggests the presence of the base of the Algonkian, if, as seems to be the case, the Harney granite is intruded only into the lower schists of the Algonkian. As here exposed, it is a coarse pegmatitic rock, its principal constituents being large feldspars, apparently albite, with patches of black tourmaline. (Hovey.) Quartz occurs both as segregated patches and in graphic structure in the feldspar. There is also a considerable quantity of muscovite. The following description, by Newton, (Newton & Jenney, p. 69) of the Harney granite is equally applicable to this rock:—

"It is granite on a large scale, with all the elements of that rock — feldspar, quartz, and mica — present, but instead of their being mixed with tolerable uniformity throughout the mass each constituent is very highly crystalline and aggregated by itself. Feldspar is the most abundant constituent and forms 70 or 75 per cent of the whole. It is always highly crystalline and sometimes exhibits large crystal faces but no perfect crystal was discovered. * * * The quartz of the granite is commonly glassy and clear, but its variation in texture and color is great. It is usually crystalline, but no crystals are found. * * * It composes approximately about 20 per cent of the granite, but is distributed with great irregularity. In many cases the quartz penetrates the feldspar mass in irregular seams or fragments, which on certain fracture planes produce the figures so suggestive of oriental inscriptions, and which have given to the variety its name of *graphic granite.*" * * *

"The mica ranges from silvery white to dark brown in color. It is always highly crystallized, and well defined hexagonal crystals two inches in diameter are very common. * * * The mineral forms only about 5 per cent of the granite, and though sometimes distributed generally through the mass, it is more often found in bunches or segregations. It was observed that it rarely accompanies the feldspar alone, but is almost always associated with quartz."

"Besides the three minerals essential to the formation of granite the only ones found in abundance are rose quartz and tourmaline. The latter is quite common and sometimes composes 3 or 4 per cent of the granite. It is usually but not exclusively associated with quartz. It is black in color, and is generally highly crystallized, though sometimes massive."

The granite dikes of the Nigger Hill region fifteen miles to the west of Whitewood Peak, while in general finer grained and nearer typical granites, have occasional pegmatitic facies which resemble the granite here described, and are probably the nearest outcrops of a similar rock. (Darton b, p. 4.)

The occurrence of the granite and schist in this place may be explained in three ways. The Algonkian may be in place under the Cambrian, and revealed by the fault, or it may be a small wedge broken off from the wall of the conduit of the laccolith and carried up with the Cambrian above, or it may be an inclusion from a great depth, brought up by the porphyry, which spread out between the Algonkian and the Cambrian, and thus the schist fragment became wedged or frozen against the bottom of the Cambrian.

The first of these explanations is hardly tenable, for the fault, though of considerable throw in the middle, fades out away from the porphyry intrusion, and hence seems to be dependent directly upon the laccolith. Also, to all appearance the Algonkian rests upon the porphyry and hence cannot be of much greater depth than is exposed in the section.

The supposition that the Algonkian is part of the underlying floor on which the Cambrian rested, brought up with the doming of the Palaeozoic sediments by the intrusion of the porphyry, has several points in its favor. (See Section, Plate 1). It is possible that, given a conduit with sloping walls, such as would be necessary for the production of an unsymmetrical laccolith, a part of the hanging wall of the conduit would be broken off and forced, by the pressure of the porphyry beneath, to cling to the base of the Cambrian above it. Although the actual contact of the Cambrian and Algonkian was not

seen, only a few feet intervened between the lower outcrop of the Cambrian and the highest part of the Algonkian. Furthermore no porphyry was found between the two rocks.

A somewhat similar case where the basal Cambrian rests on the granite has been described by Darton in the Bear Lodge range 35 miles to the westward. (Darton, b., p. 5, c., p. 4.) Here a granite mass some three miles long and three-eighths of a mile wide is overlaid for the greater part of its length by the basal quartzite of the Cambrian. This, however, differs from the case just cited in that both the granite and the Cambrian bed are themselves enveloped in the porphyry.

A possible objection to this hypothesis is that the granite and schist, being different from the Algonkian of the vicinity of Deadwood, cannot represent a part of the immediate floor on which the Cambrian was laid down. This objection, however, would be removed if we could imagine the presence of a pre-Cambrian fault between the gulch where the Algonkian occurs and Deadwood, bringing a different phase of the Algonkian to the pre-Cambrian surface — and possibly giving the line of weakness followed by the intruding Tertiary porphyry.

The third explanation — that of an inclusion up from great depths — saves us from this rather imaginative conception of an invisible pre-Cambrian fault. But here again it is not easy to imagine that such a large block could be lifted to the very top of the domed porphyry reservoir and there pressed against the lower member of the Cambrian, without an intervening layer of previously solidified porphyry. It is true that no actual contact of Algonkian and Cambrian could be seen, some few feet of talus intervening between the nearest outcrops, but if there were porphyry between, it should stand out in a ledge, being one of the most resistant rocks of the region.

The absence of granite pebbles in the basal conglomerate of the Cambrian in the Whitewood canyon laccolith, tends to support this explanation. But as the conglomerate was only found in two places, this is not very significant.

To sum up, from the available evidence, the origin of the granite and schist in this region: —

The granite rests upon the Tertiary porphyry and hence its appearance here is due to the porphyry intrusion.

It may be either a part of the floor on which the Cambrian was laid down, broken off from the wall of the conduit and carried up with the porphyry, or it may be an inclusion in the porphyry magma, brought up from great depths.

The Porphyry Sills.— Porphyry sills were found throughout the

Minnelusa (upper Carboniferous) formation, to the north and east of Whitewood Peak (Plate 2, fig. 1). This porphyry differed from that of the main laccolith in that here the phenocrysts were quartz-crystals in perfect di-hexagonal pyramids, instead of slightly rounded feldspars, as in the main mass of the porphyry. On the west side of Whitewood Creek, opposite the mouth of Sandy Creek and in the bed of the stream as well, is a large mass or stock of porphyry breaking through the Minnelusa. (Plate 3.)

The sills found in the Minnelusa to the north of Whitewood Creek, on the crest of the dome of the laccolith, were all very thin, never more than a few inches thick, and of no great extent. They were best seen in the small railroad cut near the entrance to the tunnel, north of the sharp elbow made by the Creek. The sills of the region around Sandy Creek were, as can be seen from the map, of great extent, and one at least was about a hundred feet in thickness.

The Minnelusa formation is composed of sandy limestone and sandstone in rather thin beds and overlies several hundred feet of massive Mississippian and Ordovician limestones. These latter are resistant, and, while bending to accommodate the new conditions of a laccolith beneath the Cambrian, are too compact to allow any porphyry sills to spread out in them. The Minnelusa, on the other hand, being thin bedded and composed of beds of differing texture, is particularly well adapted to allow the formation of sills.

The size of these sills in different parts of the area is evidently dependent upon the laccolithic dome. In the syncline between the two laccoliths of Whitewood Canyon and Crook Mountain to the northeast the bending of beds on different radii gives large open spaces which offer a locus for the intruding porphyry. Moreover, the cracks forming as the result of the synclinal bending would gape downwards, thus allowing more porphyry to enter and enlarge the open spaces already present in the syncline. This condition is somewhat analogous to ore deposits of the type of Broken Hills (N. S. W.) where the open spaces in a syncline have been filled with mineralizing agents instead of porphyry. On the crest of the anticlinal dome, however, a different set of conditions would be present. The beds, being of different textures and thicknesses, would bend to curves of different radii, as in the syncline, but the weight of the strata above the arch would tend to flatten out the open spaces, leaving less room for the formation of sills. Also the cracks formed, although they might be more numerous than in the syncline, would gape upwards and thus not allow porphyry to enter.

For this reason all the large sills of the area were found in the vicinity of Sandy Creek, while only small thin sills occur on the top of the dome.

Of interest in this connection are the experiments made by Howe, (Jaggar, p. 291–303) where laccoliths were formed of molten wax injected into a sedimentary series built up of thin layers of plaster, coal dust, marble dust, and sand. Here it was found that where the injection was rapid there was a marked tendency to form sills. (See especially experiments 3, p. 297, and 5, p. 300, and Plate 18, figures 3 and 5.)

Summary.— The outcrop of Algonkian above the porphyry on the side of the gulch is of interest on account of the presence of a schist different from those found in the vicinity and of granite identical with that found in the Harney Peak region many miles south. To account for this, two explanations — neither entirely satisfactory — have been suggested. It may be a part of the floor of the laccolith, carried up by the porphyry with the Cambrian in place above it; but if so it is difficult to account satisfactorily for the difference between this schist and that of Deadwood, only a few miles away. On the other hand it may be an inclusion from great depths, representing a part of the Algonkian lower than is exposed at Deadwood, brought up by the porphyry and "frozen" against the Cambrian. If this is the case it seems strange that there should be no porphyry between the Algonkian and the overlying Cambrian.

The presence of porphyry in sills in the Minnelusa formation is noteworthy as showing that, in this laccolith, the intruding magma reached a higher horizon than had been supposed. The fact of the sills being of greater thickness and extent in the syncline than in the anticline is explainable by the supposition that the laccolithic dome had already been formed before the intrusion of this porphyry and hence the syncline already formed was a favorable situation for later intrusion.

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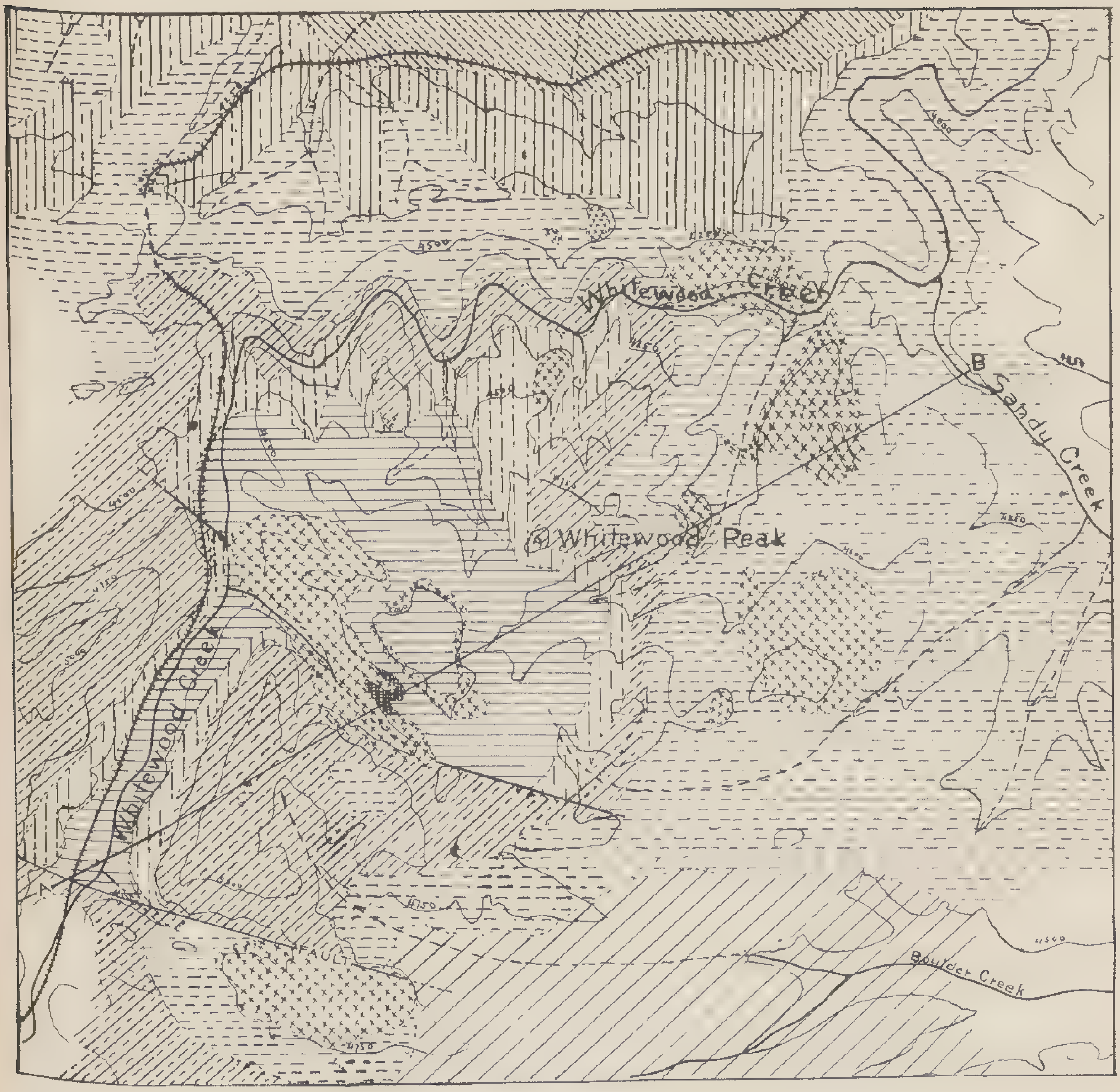
EXPLANATION OF PLATES.

PLATE 1. Geological map and section of an area three miles square, northeast of Deadwood, South Dakota.

PLATE 2. Fig. 1. Whitewood Peak from across Whitewood Canyon, showing escarpments of Minnelusa (cml), Pahasapa (cpa), and Whitewood (Ow) limestones, and Cambrian quartzite (Ꞓ).

Fig. 2. Small fault northwest of Whitewood Peak, showing Pahasapa limestone overlying the Englewood limestone and shale and the massive Whitewood limestone below.

PLATE 3. Porphyry stock, one mile northeast of Whitewood Peak.



Contour Interval = 250 Ft.

Scale

0 1/4 1/2 3/4 1 2 miles

LEGEND

- Pleistocene Gravels
- Jura-Trias-Sundance Formation
- Carboniferous {Minnekahta Formation, Opeche Formation}
- Carboniferous-Minnelusa Formation
- Carboniferous {Pahasapa Formation, Englewood Formation}
- Ordovician-Whitewood Formation
- Cambrian-Deadwood Formation
- Algonkian Schist and Granite
- Intrusive Porphyry

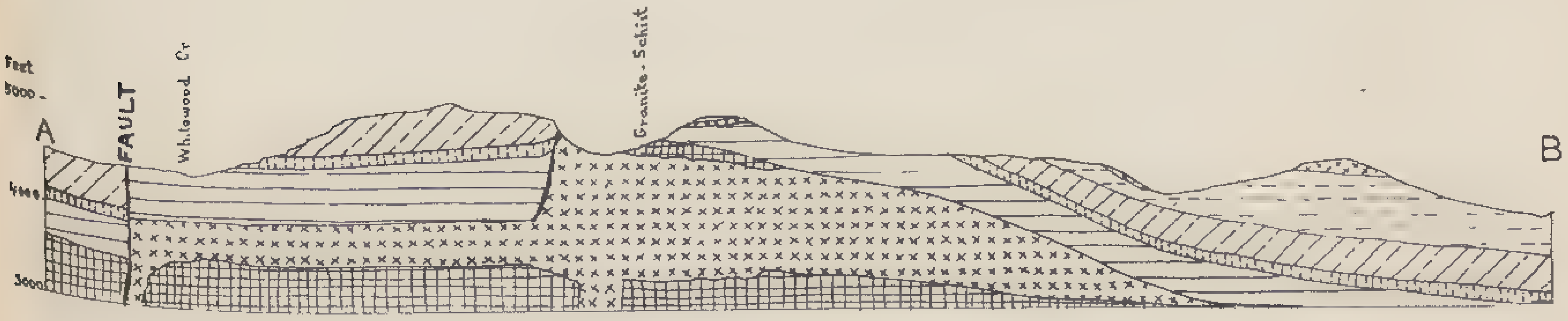


Fig.

Fig. 2

Cockayne, Boston

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Bulletin of the Museum of Comparative Zoölogy
AT HARVARD COLLEGE.
Vol. XLIX.

GEOLOGICAL SERIES, Vol. VIII, No. 6.

EXPERIMENTS ILLUSTRATING EROSION AND SEDIMENTATION.

By Thomas Augustus Jaggar, Jr.

With Six Plates.

A CAMBRIDGE, MASS., U. S. A.:
PRINTED FOR THE MUSEUM.
March, 1908.

Reports on the Scientific Results of the Expedition to the Eastern Tropical Pacific, in charge of Alexander Agassiz, by the U. S. Fish Commission Steamer "Albatross," from October, 1904, to March, 1905, Lieutenant Commander L. M. Garrett, U. S. N., Commanding, published or in preparation: —

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No. 6.—*Experiments illustrating Erosion and Sedimentation.*

By Thomas Augustus Jaggar, Jr.

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Introduction. The fundamental conceptions of river development in current physical geography are as follows:—(1) young rivers cut down their channels where the slope is steep enough to give them an active current, but where the slope is faint, the streams lay down their load of detritus and build up the surface. (2) A branch stream of a larger river has the advantage of the greater depth to which the main valley is worn. In competition with like branches of smaller nearby rivers its divide will shift faster. This doctrine is commonly applied to "belted coastal plains." (Davis.)

Catchment Basins and Water-bearing Strata. It is of course recognized that velocity of current increases with increase of volume, and where two streams have like slope, the more voluminous will have greater corrasive power. There are two very important ele-

Note:—This research was carried on in the Laboratory of Experimental Geology, Harvard University, while the author was there a teacher of Geology, and was aided by Grant 101 Elizabeth Thompson Science Fund. The author wishes to express to the Trustees his grateful appreciation of this grant.

ments in the problem, however, which have been given less attention by geomorphologists:— initial catchment basins, and initial attitude of aquiferous strata. The whole surface of an uplifted sea-bottom, for example, does not immediately become covered with streams. Rivers are extended from the old land and a limited number of new tributaries and longshore streams develop, apportioned in number to the rainfall and to the underground water supply. Their loci and spacing are dependent first upon extremely faint irregularities dividing the surface into a few flat catchment areas. After some gorges are cut, strata relatively impermeable or water-bearing are opened, and underground reservoir areas take control. When this happens if there be the faintest possible longitudinal tilt to the beds, local or general, there will be unsymmetry in the development of subsequent branches. A flat syncline of deposition with axis normal to the shore line would give mastery to any stream, small or great, cutting into aquiferous strata along its axial line. A much greater stream from the old land might cut a deep gorge along the adjacent faint anticlinal axis. It would have no power to send young branch ravines "gnawing headward" right and left. The underground pores would tend rather to drain it than to feed it, if the river cut into a permeable stratum. Hence extremely slight initial surface slopes and the underground slopes of impermeable water-bottom strata must be taken into account in any argument which deals with river piracy, divide migration, and "consequent," "subsequent," or "obsequent" streams.

Imitative Character of Rills. The subject of drainage modifications is not without experimental possibilities. The delicate rill patterns seen on beaches are but one step removed from "bad-land" valleys; the latter again are analogous to all land drainage, when due allowance is made for the effects of geological structure. Such allowance is too often neglected on the one hand, or imagined structural influence is too much accentuated on the other, as in those cases where river pattern is attributed indiscriminately to the influence of joints and faults, and residuals are believed, because of their saliency, to possess specially resistant rocks.

Purpose of Experiments. The present study deals with a series of experiments designed to perfect apparatus for reproducing rill patterns in the laboratory. In the later of these experiments some success was attained, and meanders, piracy, digitation, corrasion,

aggradation, and delta building have been reproduced in miniature. Some account is here given of the history of these experiments, which have been carried on from time to time in the Harvard laboratory for eight years. In addition, the author's last models are described in detail, as they illustrate the argument outlined above.

PREVIOUS STUDIES OF RILL DRAINAGE. The principal studies of rill pattern which have been made by geologists (Chamberlin and Salisbury, Nathorst, W. C. Williamson, Meunier) have been directed to their imitative character when preserved as fossil markings. In such a relation they frequently resemble organic forms. Daubrée (1879) believed many river systems to be controlled in development by faults and joints, and he has been followed in the United States by Hobbs (1901, 1905) and Iddings (1904) who seem to have a similar belief. Dodge (1894), from the physiographic standpoint, has pointed out the similarity of beach rills to continental drainage.

THE LABORATORY OF EXPERIMENTAL GEOLOGY (HARVARD UNIVERSITY): PRELIMINARY EXPERIMENTS. The mechanical difficulties of realizing even beach conditions in a laboratory are great. Ground breaking studies of importance were made in 1899 in the Harvard laboratory by Dr. Ernest Howe, now geologist to the Panama Canal Commission. In connection with experimental laccoliths Howe (1901) eroded domed surfaces of sand and marble dust with a coarse spray, and obtained radial drainage and infacing hog-backs.

SEEPAGE RILLS. In 1900–1901 the method was changed and instead of etching the surface of a model with a spray, various devices were used to produce seepage through a bank of sand. It was hoped that the phenomena observed on beaches might be duplicated.

In Plate 1, fig. 1, there is shown a meandering stream produced by seepage through a sand bank. A beach of sand was built on a suitable metal pan and a trench was dug along the upper margin. The trench was kept full of water which soaked the model. The oozing water gathered in two principal rills, which meandered from the time of their inception, and never showed any tendency to develop tributaries. The streams corraded profoundly even while meandering, and the complex terrace and distributary phenomena are part of a process of planation (Gilbert) uninfluenced by change of tilt.

In Plate 1, fig. 2, are shown the beginnings of digitation, coördinate with a meandering tendency. This stream, as in Plate 1, fig. 1, was

produced by seepage through an inclined sand beach. The model differed from that of Plate 1, fig. 1, however, in that it was built of alternate sedimentary layers of marble dust, clay and sand, whereas No. 1 a was homogeneous sand. The oozing waters of the main stream bed undermined water-bearing strata on the walls of its gorge. The waters so released into the valley undermined superjacent beds, starting lateral channels. The loci of these channels are interdependent, because each tributary has a potency of position dependent on an initial underground drainage area. The moment a stream flows freely it discharges the waters of a certain upslope district and that district thereafter slowly enlarges until it is delimited by boundaries which are underground divides from other drainage. Such divides are not topographic elevations in any sense; they are the boundaries of what might be called the "sphere of influence" of any stream. No lower tributary in the same up-and-down zone of flow can use from the same aquiferous stratum any of the underground waters of an area above a higher tributary; hence a lower tributary, to gain a drainage area of its own, must eat laterally until it is beyond the zone of higher tributaries, or make use of aquiferous strata stratigraphically below their level. Moreover a higher tributary is always apt to take off the underground waters of a lower, and therefore rob it in fact, though none of the ordinary superficial evidences of piracy may appear. Initial rhythm occurs where uniform undermining affects uniformly a cliff of uniform height for some distance; instance the rhythmic spacing of the four lower tributaries on the right[1] bank of the main stream in Plate 1, fig. 2. A similar notching, having a tendency to rhythm, may be seen on both cliffs which bound the widening flood plain farther down stream. The four dextral tributaries mentioned are graduated in length, the highest being the longest. The reason for this is that the highest controls the headward drainage area underground, the next lower stream is thereby impoverished of supply, and so on to the smallest. As a stream gains width it increases the number of orifices of exit of water, its volume and its underground drainage area. This process has reached its maximum in the wide flood-plain area of the main stream, which by both scour and lateral planation has opened a broad water channel beneath the flood plain. That channel satisfies the discharge of a large drainage area on either side, hence there are no lower tributaries in the cliffs bordering the plain. Wells dug in the flood plain would find abundant water anywhere representing a

[1] "Right" and "left" in this paper always refer to an observer facing downstream.

flowing sheet from under the lateral cliffs. The river bed itself is a locus of seepage wherever the stream corrades.

UNDERGROUND DRAINAGE AREAS AND STREAM SHADOW. The foregoing analysis brings out two principles which may be defined before going farther. Each tributary in this model of inclined strata, has an underground drainage area. So has every natural orifice of exit of seeping waters in nature. Every spring controls such drainage area. Every brook is apt to be a line of loci of springs, and collectively they control a certain underground drainage area. Every forking system of tributaries, on larger scales, controls a similar underground area. The supply of every river system is dependent on this underground area (King, F. H., 1899), on the one hand, and a surface catchment basin, on the other. If, as in this model (Plate 1, fig. 2), strata variously aquiferous slope with the drainage, then each impervious stratum is an underground *surface* on which are separated the underground drainage areas of different orifices. Hence there may exist underground divides dependent on initial attitude of strata, and quite independent of initial surface topography. Apparently the presence of drainage *surfaces* as distinct from *pores* favors digitation. This is shown by the contrast between figs. 1 and 2, Plate 1. This is borne out by the fact that the spray models hereinafter described also develop arborescent drainage, the drainage surface in such case being the superficial topography. In contrast to these, in a model supplied wholly by seepage (Plate 1, fig. 1), there is no initial drainage surface.

The control by a tributary of a certain drainage or accumulation area of its own prevents that area from supplying water to any orifice farther down the general slope. Whether this be a superficial or an underground area, the effect is the same. Accordingly any such lower orifice may be said to be in the *shadow* of the higher stream and its drainage area. In Plate 1, fig. 2, the lowest of the four rhythmic tributaries on the right bank is thus shadowed by the next higher, and so on. Headward development by undermining will go on by a multiple ramification of those streams which can free themselves from shadow. The development of tributaries is more difficult mouthward than headward, because the mouthward region of a straight river is always in the shadow of the headward tributaries. If a river can for any reason bend laterally, new tributaries may develop wherever a curve undermines a portion of the general slope not in shadow. This principle is illustrated in Plate 1, fig. 2. If a lower tributary can eat laterally far enough to go beyond the shadow of higher branches, it may acquire a

drainage area of its own. The outer bank of a river's main curves is the one which will naturally develop tributaries.

Flood Rills. In the model illustrated by Plate 2 an accidental development of arborescent rills on the surface was produced by flooding. The model consisted of stratified marble dust, coal dust and sand, the strata overlapping. Two faint constructional terraces had been left in the topography. It was planned to erode with seepage, but the trough at the upper edge of the model accidentally overflowed. Almost instantly, as the rush of water flowed off the surface, the drainage pattern developed as shown in the plate. The three steeper slopes show arborescent drainage, while flood plains occupy the terraces. An interesting feature of this model is the development of arborescence not from baselevel headward, but all over the surface flooded, with its maximum on the steeper slopes and in the medial region.

"Grand Canyon" Model. A considerable advance beyond earlier experiments was made in 1901 by R. W. Stone, now of the U. S. Geological Survey, and the author. A tank five feet (1.52 m) square and ten inches (.254 m) deep was used. The water was maintained at a constant level by a flood-gate. A rectangular island was built by sedimentation, 25 × 36 inches (.63 × .91 m) in area and 3 inches (.076 m) thick. Separate layers were sifted into a frame, the whole being kept moist. The model consisted of 61 very thin layers of marble dust, coal dust, clay and red lead, with three massive layers of sand each ½ inch (.013 m) thick, (Plate 3). A fine spray was produced by means of two special nozzles. These were constructed so that a fine direct jet was broken up by impact against the ragged surface of a finely punctured tin plate, fastened at 45° inclination to the line of the jet. A mist-like spray was thus thrown at an oblique angle, while the excess of water was allowed to run off. These two nozzles were arranged on opposite sides of the model so as to produce a uniform rainfall over its surface. The model was tilted, sprayed daily for some weeks, and photographed frequently. Arborescent drainage developed, deep canyons with esplanades and waterfalls were cut, and a flood plain was formed along the lower reaches of the confluent main streams which terminated in a lobate delta built out into the lagoon. A cross-section of this model, after 718½ hours of erosion, is shown in Plate 3. On the right is shown the delta in section. In the middle of the section may be seen profiles

of two cascades and a perspective view of the canyons. On the left is shown the upper margin of the model and the back slope. The three light bands in the cross-section consist of about twenty thin layers each of marble dust, coal, etc.; the darker bands are sand. During the final days of spraying the model was tilted 10 degrees.

The important part played by volume of water, as contrasted with slope, in producing erosion, is well illustrated in this model. The back-slope, shown on the left in Plate 3, had a grade of some 45 degrees, while the surface of the model sloped only 10 degrees. All the stream development was on the main surface, however, because nearly all the water which fell on the model flowed down that surface. Moreover, the underground structure sloped the same way, producing seepage in that direction, and away from the backslope. The high divide at the back margin of the model remained practically uneroded, and what water trickled down the backslope never acquired volume or load enough to do any considerable trenching. The backslope would be the equivalent of "obsequent" or infacing slopes in a coastal plain escarpment. Such slopes are commonly supposed, by reason of their steepness, to cause or give evidence of a rapid retreat of the escarpment. No sign of such retreat was observed in this model, and all of the hydrostatic conditions indicate that such a slope would absorb moisture and carry the water down the dip of the strata. It would yield no springs for the development of "obsequent" streams.

It is of interest to note in the structure of the sloping frontal delta beds the following sequence:—

Thick lower white marble dust layer.
Sand layer.
Second marble dust layer.
Upper sandy layers.

These correspond to the materials of the model in the order in which they were reached by the eroding streams, viz:—

Thick upper marble dust layers.
Sand layer.
Second marble dust layers.
Sand layer.

The lowest group of light colored layers in the original model forms the bottom of the deepest canyon sectioned. Its effect is shown in the lighter color of the highest delta beds seen farthest to the right. On a steep submarine continental slope receiving the detritus of many rivers, some such corresponding inverse sequence of beds eroded and beds deposited might be looked for.

Trickle Pattern in Clay. The experiment last described was coarse. The model was bulky and very laboriously made. The coarse sand layers were made of material the equivalent of gravel in proportion to the size of the streams developed. Hence it seemed desirable, if in any way possible, to work with finer material, so as to reduce the scale of the phenomena studied and likewise diminish the labor by making less bulky models. Plate 4 shows a pattern developed in liquid modelling clay. The phenomenon is closely analogous to the trickle of raindrops on a windowpane. A glass plate 15 × 20 inches (.38 × .50 m) rectangular, was flooded with smooth liquid clay of the consistency of syrup. The clay was "flowed" over the surface, held horizontally until it was evenly covered. The plate was then allowed to rest on one of its longer edges and raised until the surface dipped 45 degrees. It was supported in this position and left to drain. The greater part of the clay ran off and formed a pool at the lower edge of the plate. A portion, however, clung to the glass, settled, and its water tended to separate and run down the slope in drops, making clear spaces along the streams and leaving the divides opaque. Plate 4 is a portion of the upper margin of the plate, printed after it was dry by direct contact with solar paper. (The right and left are therefore reversed). For a width of five inches (.127 m) the upper margin showed an arborescent tracery on so fine a scale that from 20 to 25 streams are crossed in a distance of 7 inches (.178 m) (Plate 4). Lower down the slope distributary phenomena interfere with the arborescence, and the pattern is a complex of streaks with V-shaped accumulations of clay pointing up the slope.

A number of experiments were made with this process. In one series of plates, made under similar conditions, the duration of draining was systematically varied, so as to show all stages from the first initiation of arborescence to its completion. After the first sheet-flood run-off, the arborescence always develops near the upper margin of the plate in a definite zone about two inches from the margin. It seems to develop all at once and to grow very little thereafter. This is to be expected, as there is no source of added water, and nothing to erode when the glass is reached. There is interference of adjacent streams in many places, but the control of initial drainage basins and of "shadow" are clearly shown. The trickle pattern is complicated with capillarity and much of it is mere drop-trickling. It shows, however, that the tendency to digitation may be studied on a very small scale, and these experiments led to an effort to produce something intermediate between these too quickly drained clay films and the

coarse spray model illustrated by Plate 3. The desideratum would be a model of some very fine material like clay, with an impalpable but continuous moistening of the surface, and sufficient thickness to permit the development of a distinct relief under erosion from the resulting rills.

Models Sprayed with Atomizers. Such conditions were finally realized by using the finest kind of crushed rock — slimes from a stamp mill — and spraying with atomizers. The atomizers used were the ordinary bottle style used in a barber-shop. Air pressure was maintained at about 10 pounds (ca. 4.5 kg) per square inch (625

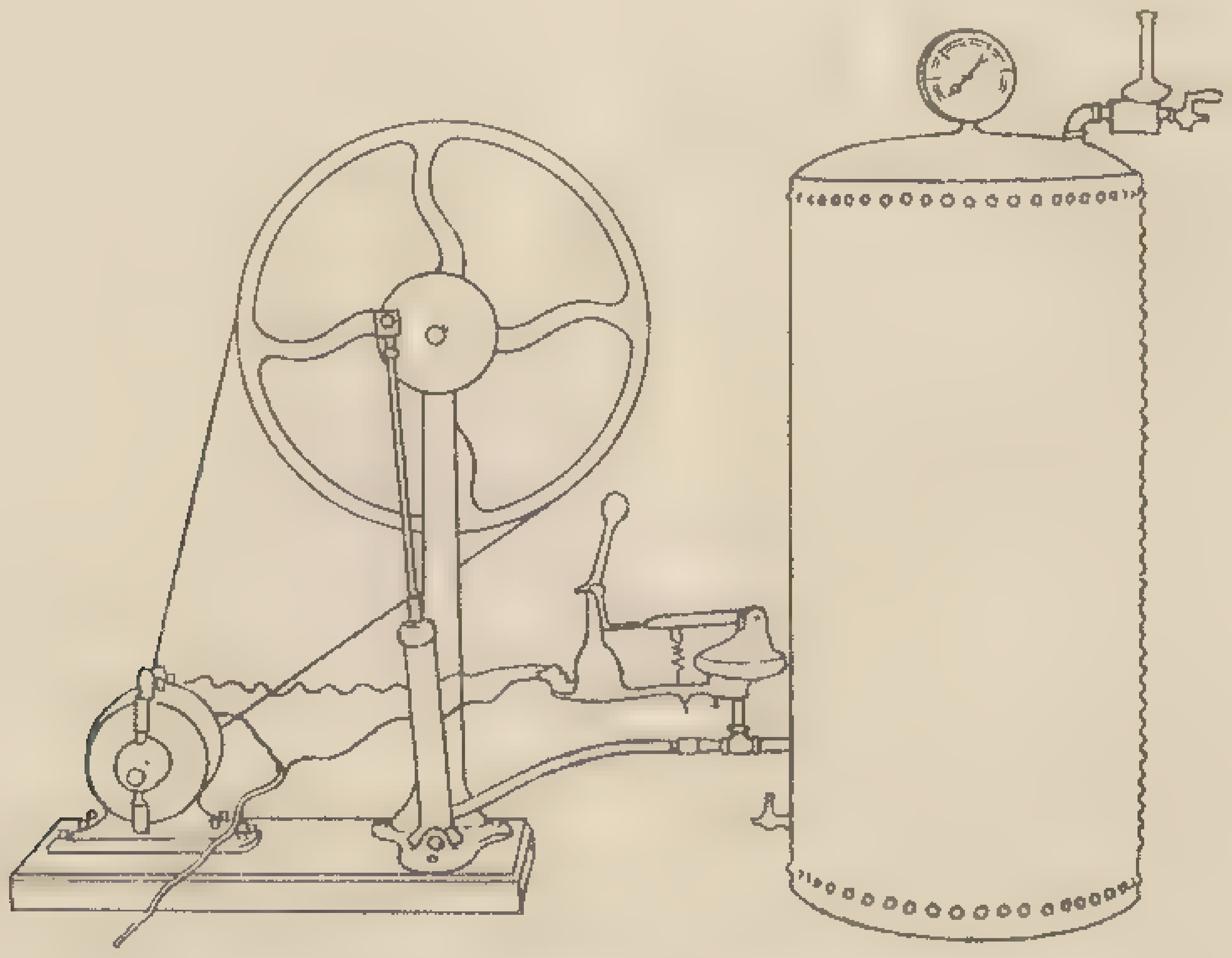

Fig. 1. Electric Air Compressor.

sq. mm.) while two atomizers were in operation. The apparatus for compressing the air is shown in Fig. 1. A $\frac{1}{6}$ h. p. electric motor operates a single-cylinder air-pump. The air is compressed in a five-foot tank provided with pressure gauge and an automatic shut-off valve which may be adjusted to stop the motor at any required pressure and start again when pressure is reduced. A rubber tube from the tank carries the air to the atomizers which are each provided with independent cocks. This apparatus may be obtained of dealers in barber's supplies.

A model of slimes was built [1] as follows:— a plate of glass $6\frac{1}{2} \times 8\frac{1}{2}$ inches (.165 × .216 m) rectangular was placed on the bottom of a deep ash-pan. A quantity of the slimes was stirred in water and the

[1] The laboratory work of this and the last experiment was done by Mr. H. G. Ferguson, now government geologist in the Mining Division, Bureau of Science, Manila, P. I.

turbid mixture poured into the pan on the glass and left overnight. The slimes settled on the glass in a layer about ½ inch (.013 m) deep. The slime-covered plate was removed and supported at a tilt of 20 degrees, one end resting on a brick, the other on a sheet of slate. A portion of the lower edge of the model fell off abruptly, the remainder rested on the slate, which was horizontal. The sprays from the atomizers were now turned on and in two hours the drainage pattern

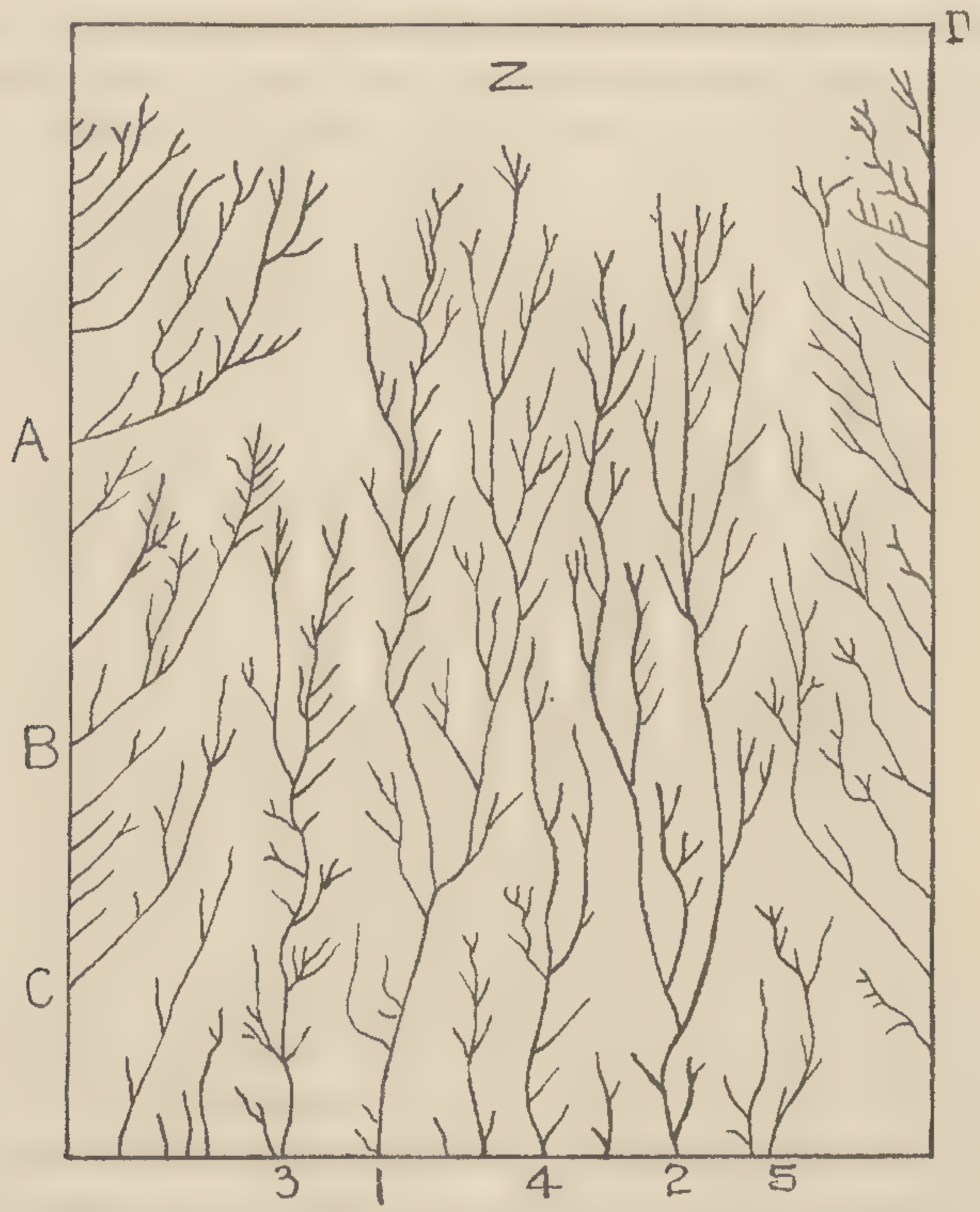

Fig. 2. Slime model. First stage. Sprayed with atomizers. Tracing of Plate 5, fig. 1.

shown in Plate 5, fig. 1, was produced. Continued spraying produced more mature topography, with deeper canyons on the side of the steep fall-off and flood-plains at the mouths of the rills on the opposite side. (Plate 5, fig. 2.)

An analysis of the drainage in Plate 5 shows a number of rhythmic features (Fig. 2). The model differs from those of Plate 1 in that the

eroding waters were all supplied from the surface. The homogeneous model was soaked and the excess of superficial water flowed off. Under these conditions the controlling drainage areas for individual rills are true catchment basins. The upper margin of the model (D, Fig. 2) is free from corrasion; here the waters accumulated, flowing down the slope until individual streams gained velocity and load sufficient to trench. Each trench then became, by reason of its depression below the general level, the medial line of an elongate drainage area, delimited by superficial divides. Lateral tributaries have tendency to parallelism and rhythmic spacing according as the general slope, initial sheet-flood, and valley-slopes were uniform. The angle of junction, in plan, of tributary and main stream in this model varies from 25 to 28 degrees. Parallel sets of spurs and streams occur in many places marking local rhythms; these are best seen by holding the plate obliquely sloping down from the eyes, and sighting downstream along the main rills. The spurs are thus seen to be equally spaced in many parallel sets related to the general slope rather than to individual valleys. There are frequently parallel features of this sort tributary to different mains.

The most marked parallelism and rhythmic arrangement is shown at the right border of the plate (A, B, C, Fig. 2). This may be viewed as a series of tributaries to the straight fall-line at the border. Three sets of streams shaped in plan like half candelabra are seen, one above the other, the highest (A) the largest. For each group, the lowest stream is compelled to eat laterally into the model farther than the next higher, and so on, in order to acquire its own drainage area. When such a stream is beyond the area which is *in the shadow* of the drainage basin next above, it wins the water of an oblique upslope district, and the drainage from that district unites in a channel which makes a distinct bend with the initial lateral channel. The bends up the slope, for the same group, are progressively nearer the fall line. The whole of group B is clearly in the shadow of group A next above. The highest stream of a lower group is prevented from development by the proximity upslope of the group next above, which catches all the upslope water. The stunted growth of the highest stream gives an advantage to the next below which acquires a longer drainage area, and the third still longer. In this respect each group is like the uppermost group, the form of which is clearly determined by the margin of accumulating rainfall Z at the upper edge of the plate. The larger rhythm of the three groups does not follow the same law, for there the upper group A is the largest. The reason for this is that the upper

group, from the time of inception of trenching, had the waters of the upper margin to draw on, whereas the lower streams stood in its shadow. Its own capacity for trenching on across the plate was delimited by competition with slopeward streams, Nos. 1 and 2 of the medial zone, of like grade with itself. In spite of the lateral stream's advantage in fall, the increasing obliquity of its course rapidly reduced its slope. Therefore, with like volume of upper sheet flood, its divide finally became adjusted to medial streams which possessed the advantage of direct flow down the slope. The larger rhythm of the three groups, A, B, and C, appears to have been propagated *down*, not up, the slope. The rhythm of streams flowing off the opposite or left-hand side of the plate is of a different sort, with five major streams of increasing length from top to bottom of the plate.

The main medial streams, 1 and 2 (Fig. 2), and the side streams, show signs of having either shadowed or beheaded the three subordinate medial streams 3, 4, and 5. Nos. 3 and 5 appear to be shadowed by the right and left side streams, respectively, No. 4 appears to have had its right fork beheaded by the left tributary of No. 1, and its left fork by the right tributary of No. 2. Considering the side streams as tributaries of the right and left fall lines as though the latter were two master stream courses, the two fall lines may be considered to have propagated across the plate the rhythmic arrangement observed. Shadowing 3 and 5, they left space for 1 and 2: 4, however, in the middle, was overshadowed by unequal competition with its two rivals.

The process of shadowing begins with the first determination of drainage areas before distinct channels have been eroded. The process of beheading or capture takes place after channels have determined local competitive base levels. The result of competition is determined for the same general zone by relative volumes of water. Beheading is accomplished by undermining headward. Shadowing is accomplished from above mouthward in a very early stage of the development of drainage. Probably on a mathematically uniform surface with uniform conditions, shadowing is a rhythmic process involving many miniature or embryonic beheadings. The theory of arborescent stream development is dependent on such a rhythmic process. The writer believes a complete statement of the mechanism of this process has still to be worked out. Like the many processes of mottling, rippling, wave motion, and bilateral, concentric, and radial symmetry in nature, the development of digitate drainage is a simple group of rhythms in its ideal form, but probably never occurs simply in natural examples. Nevertheless, probably the

cases so often described of parallel tributaries in nature, supposedly caused by joint systems, are generally an original or superposed rhythmic tributary system controlled by the law of drainage rhythm. The

Fig. 3. Stream-robbery model, ultimate rill pattern. Tracing of Plate 6.

object of such experiments as those here described should be to reduce each element in the problem to its simplest form, and to vary one

condition at a time, until the primitive types have been discovered. To this end future experiments must be directed — not toward the imitation of complex landscape conditions. The just interpretation

Fig. 4. Condition at 10.50 A. M.

of problems in river drainage can be rigorously attacked only after the primitive types have been worked out experimentally and some careful study given to the influence of each variable in the process. The

experiments hitherto described in this paper show results which are still far too complex, but they point the way.

STREAM-ROBBERY MODEL. The last experiment, the results of which are shown in Plate 6, produced an interesting illustration of stream robbery. The size, material, and method of this model were like those of the next preceding (Plate 5), the thickness slightly greater. The cracks shown in the photograph were the result of drying and should be disregarded in the discussion. Just as in the model of Plate 5, the drainage which developed left a clear zone of accumulation above, lateral streams formed on the two sides, and long straight slopeward streams formed medially. The ultimate stream pattern is shown in Fig. 3.

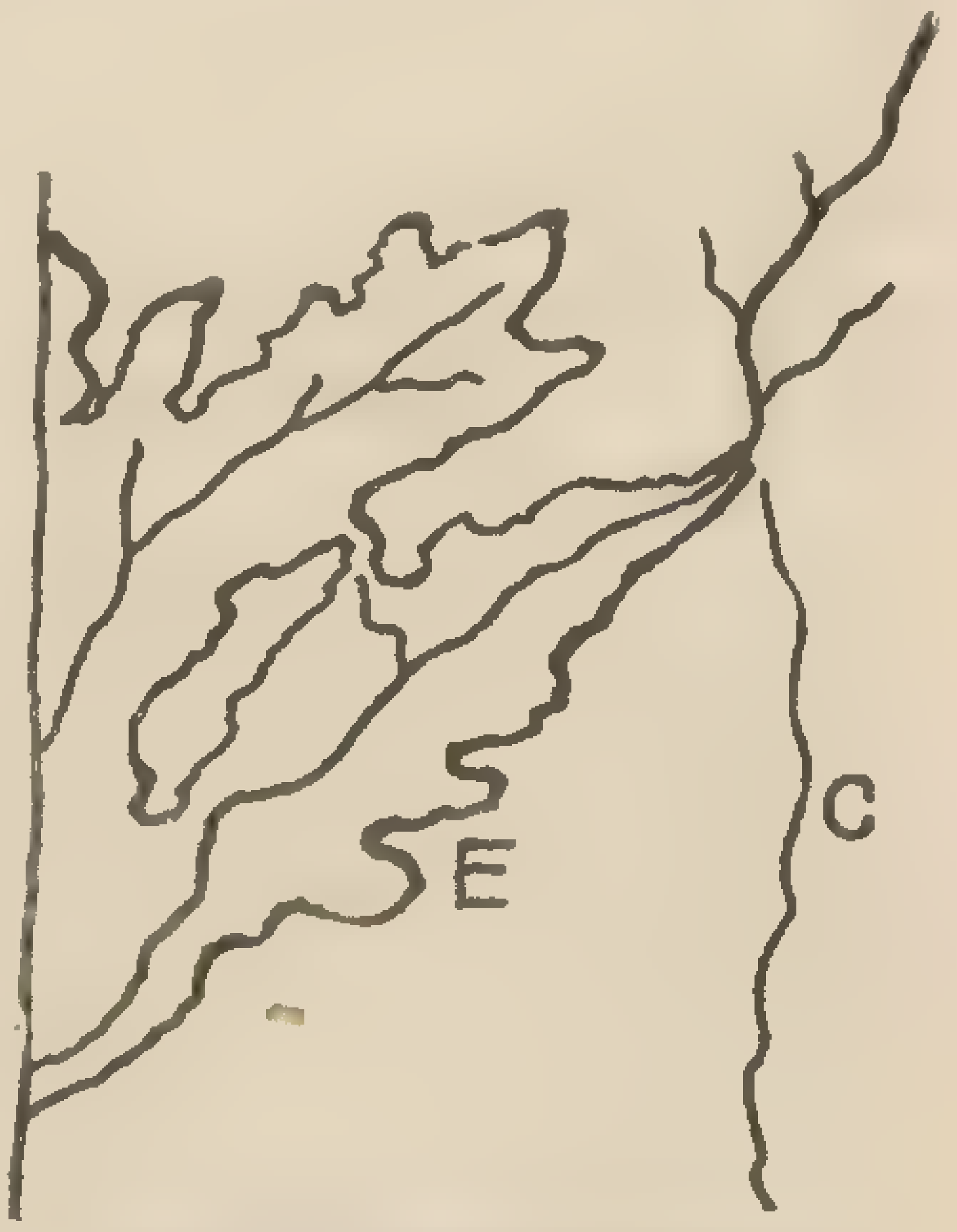

Fig. 5. Enlarged sketch of stream E at moment of capture 11.45 A. M.

At the end of the first day's spraying the right side streams were about like the left ones shown between R and the left edge of the model. That portion of stream E above the letter E was the headward portion of stream C. There were thus three principal medial streams initially. There was an initial difference of baselevel assumed whereby stream R fell off abruptly at its mouth F, whereas M, B, and C flowed out onto a flat plain P. As a result R became entrenched after the same fashion as the side streams. M, B, and C were depositing their loads and forming floodplains from about the zone of the letter M downwards. The right side stream E, having an abrupt fall-off at the edge of the plate, became entrenched and so possessed a greater fall than the sluggish and relatively overloaded C. Consequently E undermined its way headward rapidly.

On the second morning of the experiment (the spray was turned on for three or four hours each day) E, pushing headward, captured C. Fig. 4 shows a rough sketch of the model at 10.50 A. M., and Fig. 5 shows the effect at the instant of capture. The captured district of C at once revived and entrenched itself and the swollen stream E ate its way across the old floodplain of C. The lower part of C became quite inactive, being effectually shadowed by its captor. The latter (E),

however, made no great headway in extending its new headwater basin, because it in turn was shadowed by the next side stream above. The latter controlled a broad portion of the accumulation zone, and being at no disadvantage as to fall, yielded nothing to E. Fig. 3 and Plate 6 show the final result.

The other features of this model which deserve some notice are the symmetry of M (Fig. 3) in contrast to the unsymmetry of R. M is a typical medial stream which has developed freely with a delicate pattern of arborescence. R has had its left bank shadowed by the left side-streams from the first inception of drainage. The left side-streams possessed an advantage in quicker fall to baselevel, consequently they appropriated the waters of the whole area to the left of R, and nothing was provided whereby R could develop left-bank tributaries. R was not so shadowed to the right, where it controlled the accumulation area A over the space between M and the left side-streams. Its right tributaries dominate the space between R and M in a fashion similar to that whereby the left side-streams control the space between the left edge of the model and R. Probably there was a faint initial slope from M left-ward in the original construction of the surface. R was not captured by the left side streams because it was enabled by a low baselevel to trench and maintain a divide on its left bank even though it could not gather water from a wide enough lateral area to develop important tributaries.

Discussion of Principles. The foregoing experiments suggest many questions and answer few. They are based on the assumption that the extraordinary similarity of the rill pattern to the mapped pattern of rivers is due to government in both cases by similar laws. The writer recognizes the fact that in drawing analogies, only the mechanism of falling, running, and seeping waters is imitated, and not the erosion mechanism resulting from degeneration, winds, vegetation, rock-joints, and other phenomena which complicate the problem in nature. He believes, nevertheless, that river, creek, brook, rill, spring, and underground water coöperate in an orderly system of land sculpturing related to structure. This system implies a mechanism hydrostatic, corrasive, and depositive. Physical geography has produced valuable studies of form, and has classified forms in accordance with inferred processes of corrasion and deposition. But physical geography has neglected hydrostatics, and has not quantitatively nor experimentally investigated the processes inferred. This paper will have accomplished its purpose if it starts certain funda-

mental lines of investigation connected with land drainage. These are suggestive and qualitative, as the experiments have not yet progressed to the quantitative stage.

Drainage areas and stream shadow have been discussed on p. 289; the presence of drainage surfaces essential to arborescence on p. 289; the importance of volume as contrasted with slope on p. 291; the inverse relation of deposits to beds eroded on p. 291; parallelism and rhythm on p. 295 and thereafter; the comparison of capture and shadow on p. 296; and in several places reference has been made to the undermining of surfaces whereby tributaries arise and whereby a propagation both upslope and downslope of certain rhythms may start from an intermediate region. In the trickle-pattern on glass, V-shaped deposits pointing upstream form in a mouthward (p. 292) zone of overload. In most of the experiments there is an upper zone of water accumulation without channelling. Parallelism and rhythm in distribution of tributaries and spurs may by the mechanism of arborescent drainage be satisfactorily accounted for, without any influence of parallel rock joints (p. 297).

In Plate 5, figs. 1 and 2, and Plate 6, a marked characteristic is the presence of much larger portions of the original surface uneroded near the lower edge of the models than in the middle right-and-left zone of many tributaries. The general surface is more lowered in the middle zone than in the upper or lower zones. The middle zone is the region of maximum corrasion, maximum removal of material, and maximum maturity of topography. The interstream divides have been lowered below the original surface level, whereas the original surface level is still preserved in the flat interstream uplands of the lower part of the models. Hence the general upland surface is bevelled headward for a certain distance from the region of the mouths of the streams. This would give it a flat catenary profile from the headward district mouthward.

This profile would be uniform wherever measured. In Plate 5 nineteen or twenty stream depressions would be crossed from right to left in the middle zone and about twelve in the lower zone. Interstream divides in each case rise to a common level. The relief is greater in the lower zone. This is contrary to the prevalent conception, that would expect least relief and greatest maturity in the lower zone (Tarr, 1898). Bevelling and uniformity of crests in the same zone have been discussed by Tangier Smith (1899). He has developed a law of slopes as follows: summits follow slopes, and slopes are dependent on the rate of cutting of the streams at their foot. "If the alti-

tude and rate of cutting in neighboring streams of the same class are approximately the same, then the adjacent divides should approximate equal altitudes" (Tangier Smith, loc. cit., p. 164). "If at the beginning of the cycle of erosion the upland sky-line is markedly irregular, * * * it will depend on circumstances whether or not the uplands will tend to approach uniformity of altitude after graded slopes have been attained" (p. 170). "Adjusted slopes are graded slopes" (p. 165). That slopes tend to become graded and equalized, and that summits or crestlines follow the lead of adjacent slopes is a fact of observation clearly stated by Tangier Smith and further illustrated by the models under discussion here. But Tangier Smith throughout his paper has failed to mention the controlling feature of the process, namely, underground water. The underground water-surface varies with the topography, rising higher under the higher divides and approaching the valleys to form springs. (King, 1899, p. 97–99.) On the slopes adjacent to higher water-table, there will be higher hydrostatic spring pressure and consequently more undermining. Other things being equal, therefore, a high water-table tends to pull down adjacent slopes and consequently, by Tangier Smith's law, lowers superjacent summits. When the water-table level, and with it the summit level, equal those of neighboring divides, the spring-pressure is equalized and the opposing slopes of a valley become adjusted. Accordance of summit levels is probably largely controlled by this process (see also R. A. Daly, 1905, p. 105), with the tree-line and snow-line as correlated levels. A corollary of this statement of the levelling controlled by the water-table is that in a zone of overloaded streams depositing on flood-plains, the water-table may be dammed back into a relatively high position in the low interstream divides. If this be true the profile of the water-table from head-zone to mouth-zone along an interstream divide line should be concave upward with the two ends relatively higher than the middle portion above the catenary curve of the adjacent stream-beds. The water-table will thus have a headward bevel like that of the general surface mentioned above (p. 301) and shown in Plate 5. It should be noted, however, that a headward bevel is different from a headward slope. While still sloping mouthward, the underground water-surface is bevelled headward to the zone of maximum number of tributaries, because the divides in that direction are lower relatively to the original upland surface.

No attempt is made in this paper to discuss "peneplanation," meandering, or the mechanism of flood-plain aggradation. It is

believed by the writer that bevelling of divide surfaces to produce even sky-lines has been frequently confused with planation in works on geomorphology. Planation, where it is not marine, requires a flood-plain. (See Gilbert, G. K., 1880, p. 120.) True fluviatile planation is due to lateral corrasion and the test for it is the presence of facetted surfaces across diverse structure, where glaciation or marine planation are positively absent. It is to be hoped that the complex mechanism of planation may some day be subject for the experimental method.

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EXPLANATION OF PLATES.

PLATE 1. Fig. 1. Seepage streams in unstratified sand. Original 18 × 24 inches (.457 × .609 m).

Fig. 2. Seepage stream in stratified sand. Original 18 inches (.457 m) delta front to head of stream.

PLATE 2. Arborescent drainage formed by sudden flood run-off.

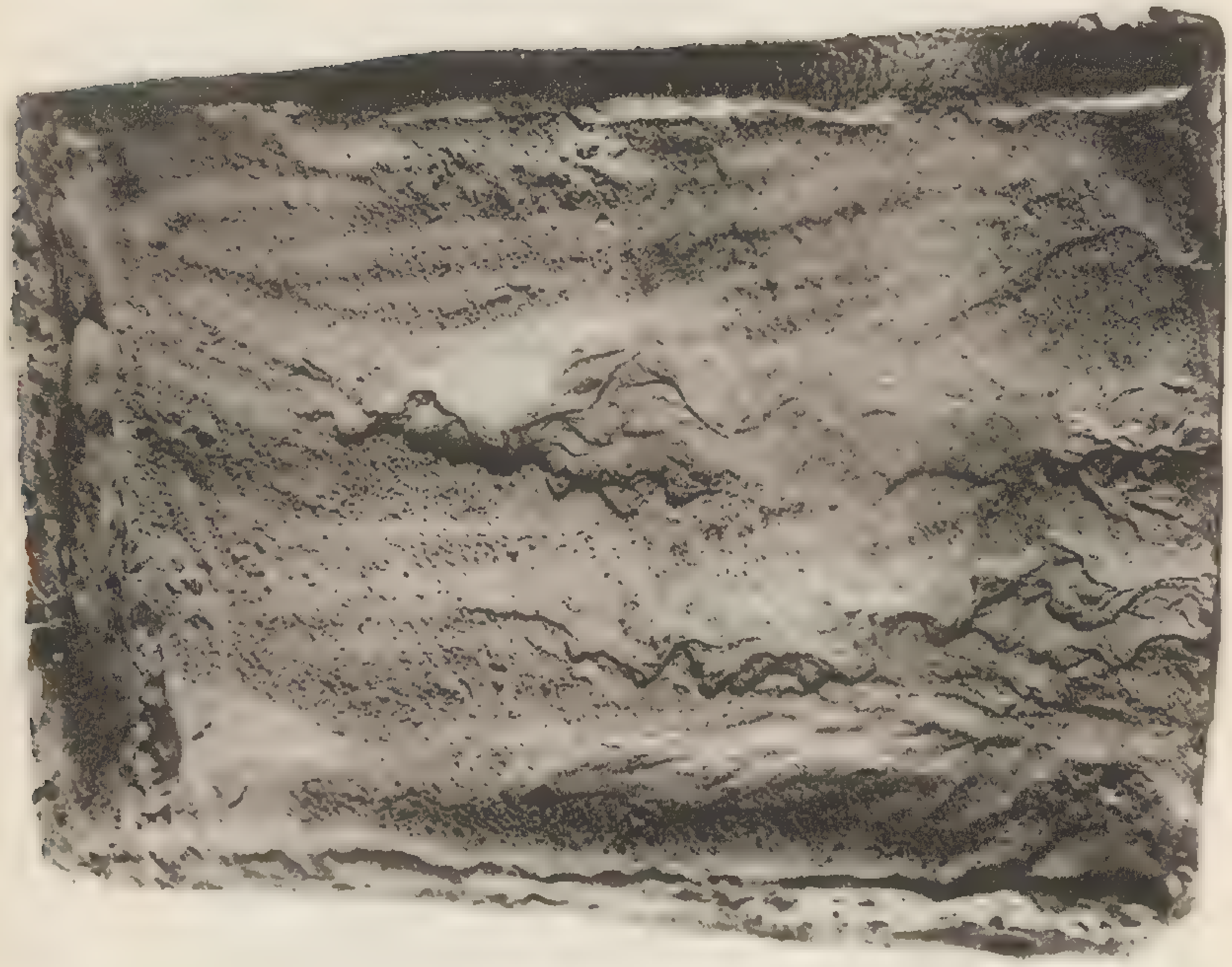
PLATE 3. Stone's "Grand Canyon" model. Original 48 inches (1.22 m) long. *Note.* Bend in lower bands is apparent, not real, and is due to the perspective of a curved surface in section.

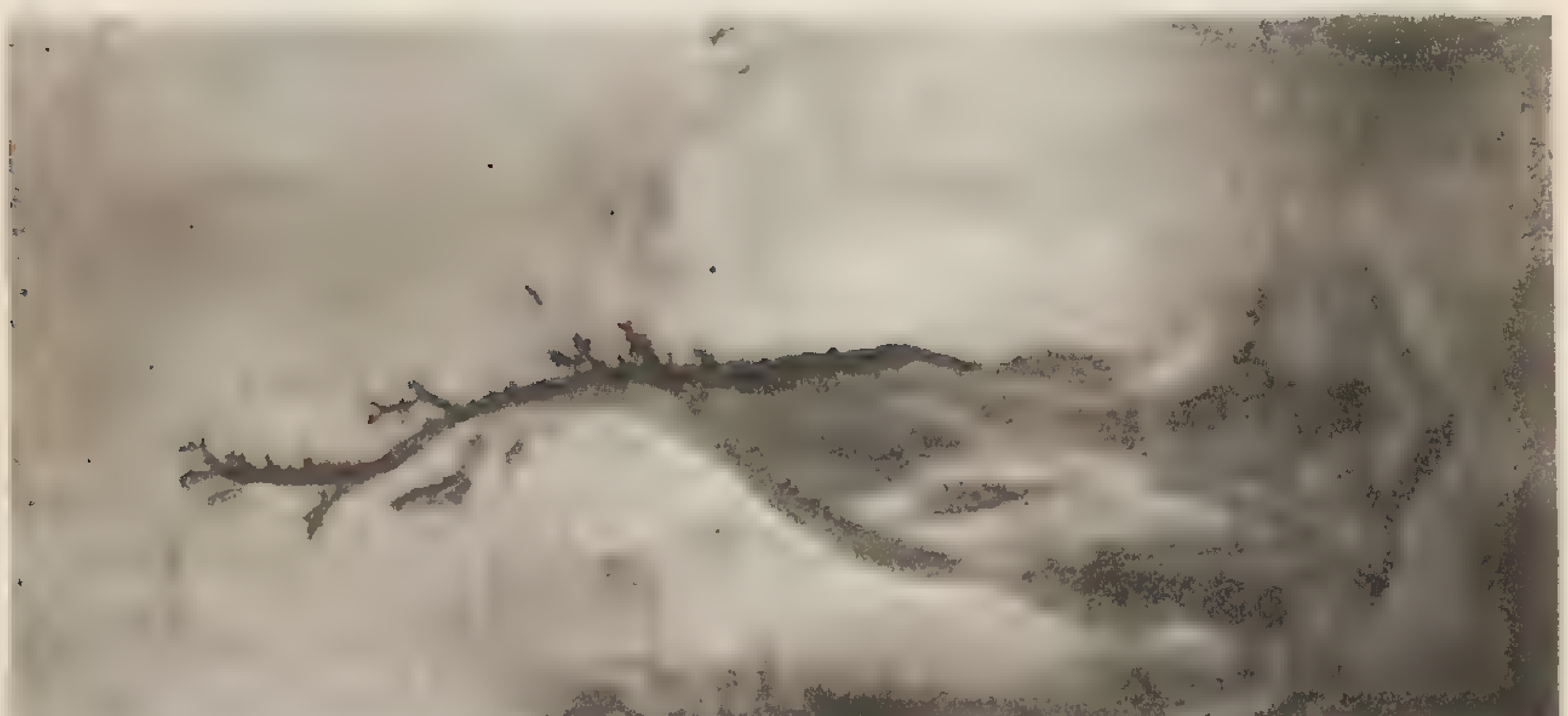
PLATE 4. Arborescent trickle-pattern formed by tilting a surface covered with liquid clay. Tilt 45°. Actual size.

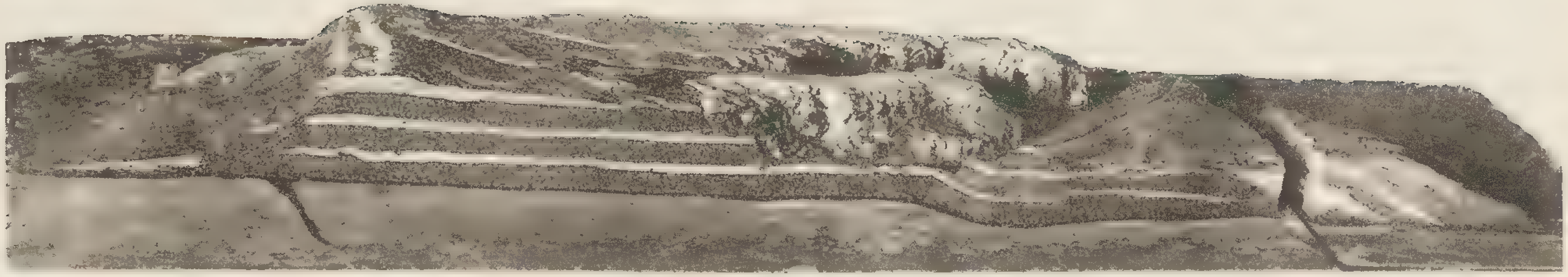
PLATE 5. Fig. 1. Slime model, first stage. Sprayed with atomizers. Original 6½ × 8½ inches (.165 × .216 m).

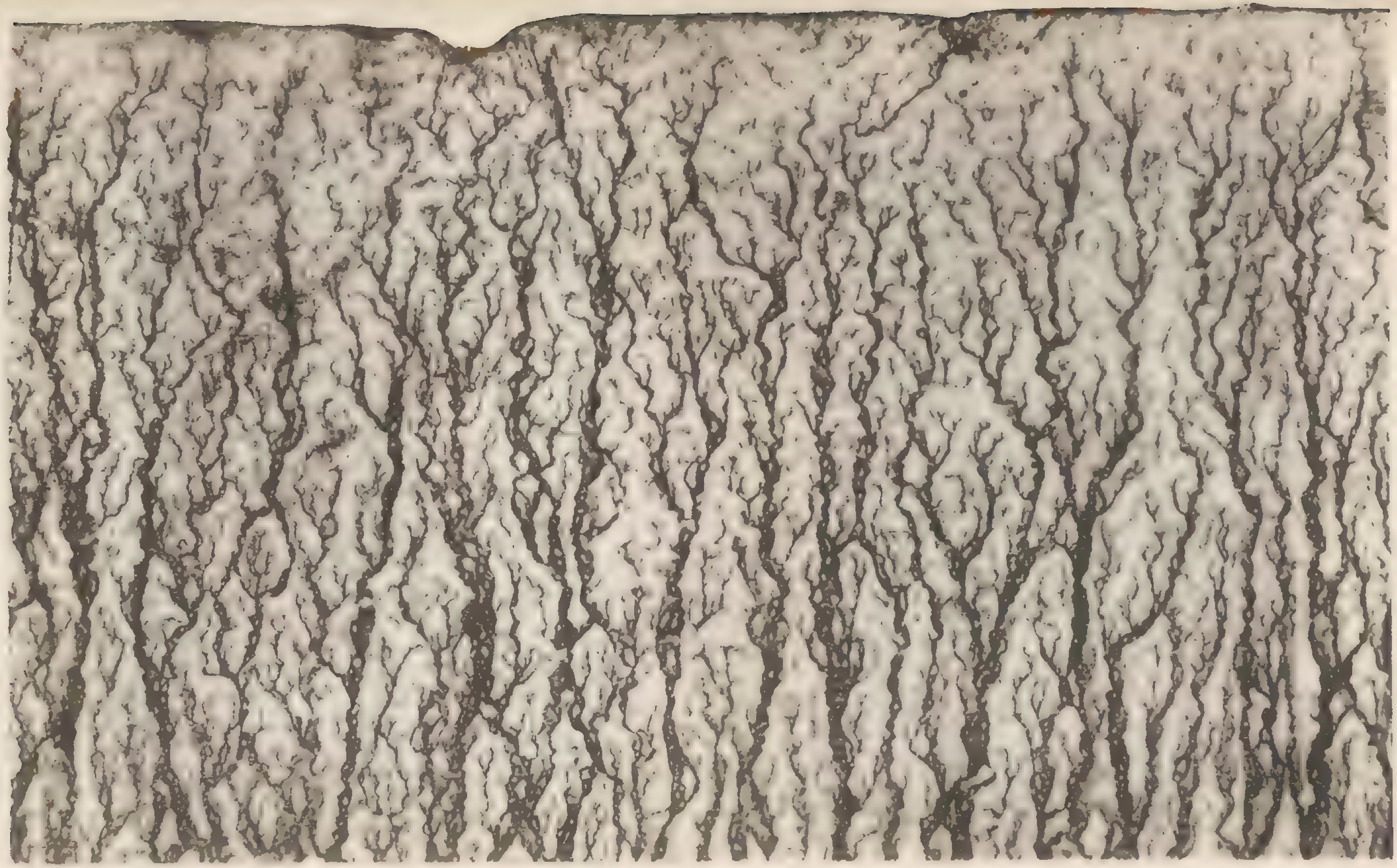
Fig. 2. Slime model, second stage.

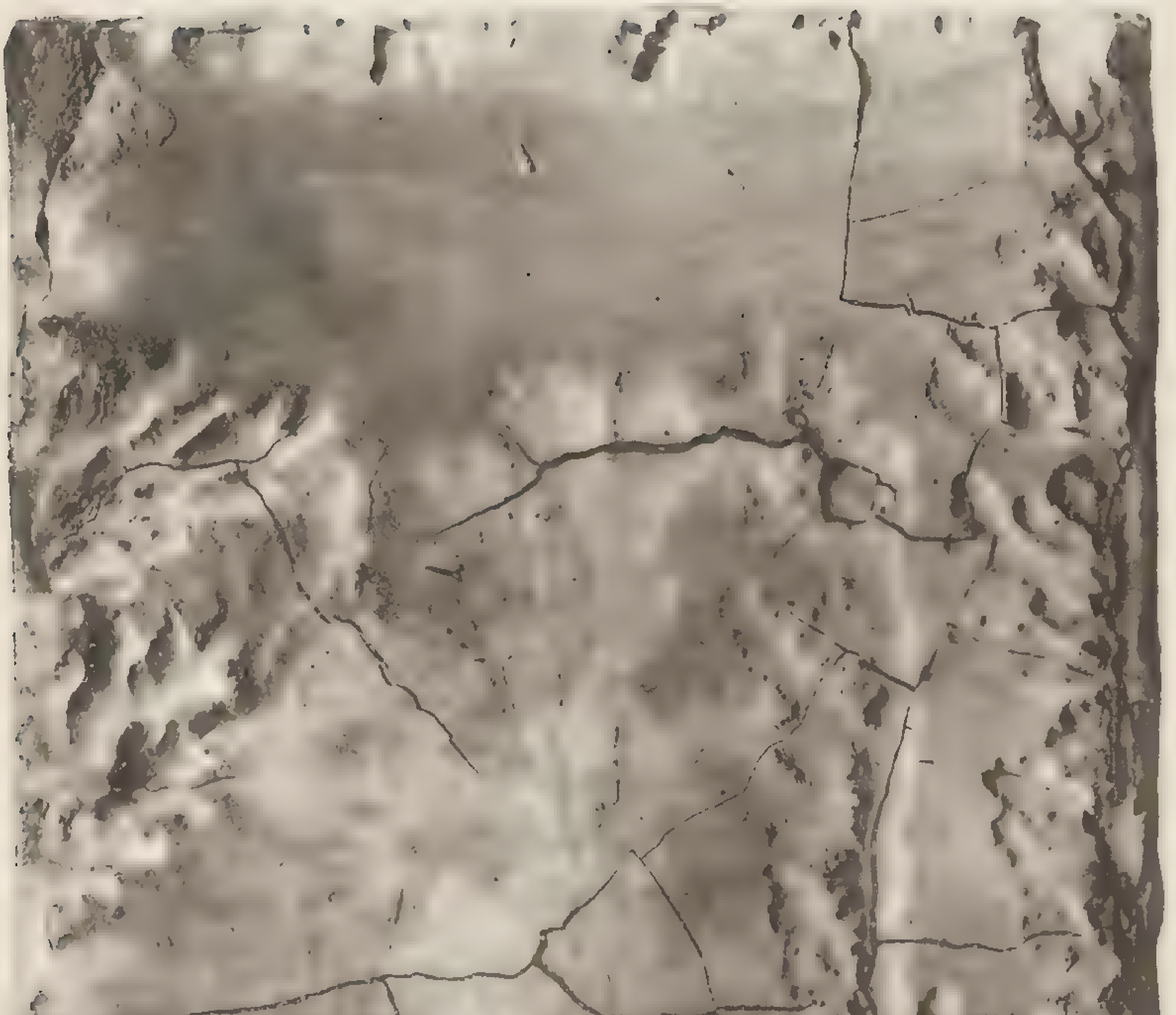
PLATE 6. Slime model illustrating stream capture.











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GEOLOGICAL SERIES, Vol. VIII, No. 7.

SOME LATE WISCONSIN AND POST-WISCONSIN SHORE-LINES OF NORTHWESTERN VERMONT.

By Herbert E. Merwin.

With Three Plates.

CAMBRIDGE, MASS., U. S. A.:
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CAMBRIDGE, MASS., U. S. A.:
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No. 7.—*Some late Wisconsin and Post-Wisconsin Shore-lines of North-western Vermont.*

By Herbert E. Merwin.

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INTRODUCTION.

The investigation upon which this paper is based was made during the summer of 1906. The work was done as J. D. Whitney Scholar for 1906, under the direction of Professor Woodworth, to whom I am indebted for many suggestions, especially as to field methods and interpretations. The field expenses were paid by Harvard University from the Josiah Dwight Whitney fund for geological field study. Mr. Harold C. Durrell of Cambridge, Mass., accompanied me at his own expense during most of the summer, very graciously assisting me in many ways.

The district studied includes chiefly that portion of Vermont which lies north of the middle of the state, and west of the divide between Lake Champlain and the Connecticut River. The work was extended to Shefford Mountain and Brome Mountain in southern Quebec.

The chief rocks of this district are metamorphic. The dominant structures, belts of gneiss, schist, and limestone, strike N. N. E. After the surface of these rocks had been maturely dissected, it was glaciated and, along the western part, depressed below sea-level, and partly buried by marine and fresh-water deposits which are largely of glacial origin. In many of the valleys further east there are large bodies of water-laid glacial materials. Changes of local water-levels during the retreat of the ice-front, and successive elevations of the region (of which the area under consideration is a part) have lead to a considerable dissection of the deposits just mentioned.

In describing in more detail those parts of Vermont and Quebec with which we are concerned, it is convenient to divide the area on a topographic basis into an eastern highland, which includes part of the Green Mountain Highland; and a western lowland, which includes the southern part of what may be called the Champlain Lowland (Plate 2, fig. A).

The Highland.— The highest parts of the main ridge of the Green Mountains are in the highland part of the area. Several points on the ridge are over 4,000 feet in altitude. Mt. Mansfield, which occupies a central position in the area studied, rises 4,364 feet above the sea. Through this ridge and lower ridges on the east and west, the three largest west-flowing rivers of Vermont have cut deep water-gaps. The depth to which these gorges were cut before they were partly filled with glacial materials is not precisely known, for the glacial materials have not yet been sufficiently removed or explored. South of Mt. Mansfield where the Winooski River has cut through the ridge the gravelly stream bed is less than 330 feet above the sea. North of this mountain the bed of the Lamoille River is scarcely 150 feet higher.

Several of the longitudinal subsequent valleys east of the main ridge are but little higher than the water-gaps through which they are drained. For example, the valley next east of Mt. Mansfield, the northern part of which drains to the Lamoille River, and the southern part to the Winooski River, is only 740 feet in altitude at the divide on the floor of the valley, between these streams.

The northern ends of some of the longitudinal valleys northeast of the one just described drain northward from similar low divides into Lake Memphremagog, thence into the St. Lawrence River; some of the valleys southeast, drain southward through branches of the White River, into the Connecticut River.

The Lowland.— The lowland part of the area studied is bounded

on the east by the high ridge of the Green Mountains, and on the west by the Adirondack Mountains; at the south it narrows and merges into lowlands of a similar character in the middle Hudson valley; at the north it is continuous with the thousands of square miles of almost dead level clay plains south of the St. Lawrence River. Above the plains in Quebec several igneous stocks rise. Brome Mountain and Shefford Mountain are two such stocks situated about 25 miles north of Vermont. Below the level of the plains there is an area extending the entire length of northwestern Vermont which was not completely filled to the general level by glacial deposits. This area is occupied by Lake Champlain. The surface of the lake is 96 feet above the sea, according to Gannett's (1906) Dictionary of altitudes.

THE SHORE-LINES.

PROBLEMS STATED.— The problems in mind when this study was begun may be stated as follows:—

1. What evidences are there of abandoned Pleistocene shore-lines on the eastern side of the Lake Champlain drainage basin?

2. Are such shore-line features as may be found, associated with local bodies of water, or may they be correlated with shore-lines already made out in the western part of the Champlain district?

3. Did any of the Pleistocene lakes which once occupied valleys now draining westward into Lake Champlain drain eastward into the Connecticut River?

PREVIOUS STUDIES.— C. H. Hitchcock and others ('61, p. 93–191) early mapped and described many terraces and so-called shore-lines of northwestern Vermont. Later, Baldwin ('94) studied some of the evidences of submergence along the eastern shore of Lake Champlain, and Chalmers ('98, p. 12–19) makes reference to beaches in southeastern Quebec. Woodworth (1905) has brought together the results of his own observations and those of others in the Lake Champlain district. I give here a summary of the history of the body of water which occupied the valley of Lake Champlain during the retreat of the Wisconsin ice-sheet, as such history has been sketched by Woodworth.

While the southern end of the ice-tongue which occupied the Champlain valley stood in the vicinity of the present divide between the Champlain and Hudson valleys, a body of fresh water known as Lake Albany bordered the ice-tongue, and drained southward. At a later time the waters of the southern part of Lake Albany were drained away, but the waters of the northern part were held in at a lower level than the original level by a barrier across the basin near Schuylerville,

N. Y. This smaller lake has been called Lake Vermont, or Glacial Lake Champlain, for from this beginning it continued to extend northward across Vermont in the Champlain valley as the ice-front retreated. The highest level of this lake was determined by an outlet just east of Quaker Springs, N. Y. This stage of Lake Vermont, Woodworth (according to a verbal statement to the writer) would now call the Upper Coveville stage. A rather gradual lowering of this lake took place until an outlet near Coveville, N. Y., at a level 100 feet lower, inaugurated a period of nearly constant level, known as the Coveville stage. The ice-front now stood somewhere between Port Kent and Street Road, N. Y.[1] (opposite the southern third of the Vermont area which is under consideration).

After the lake stood for some time at this level, during which time the ice-front was continuing to retreat, another outlet, through the valley of Wood Creek, took the drainage of the lake and lowered the lake-level another 100 feet. This is the lowest outlet which has been discovered for Lake Vermont. The probabilities are that the subsequent lowering of the lake-level was caused by the leaking out of water toward the north, around or beneath the ice. When the ice no longer formed a barrier across the northern end of the Champlain valley the sea had free access to the present site of Lake Champlain, owing to the fact that the land was depressed at the north. The amount of depression at the site of the present foot of Lake Champlain was about 450 feet. This depression was of the nature of a tilting, for the head of Lake Champlain was not then below sea-level. Since the sea first came into the valley there has been uplifting at the north so that the shore-lines developed at that marine stage are now inclined toward the south at the rate of about 3.65 feet per mile.[2] This tilted plane is the upper marine limit.

All the shore-lines made at the different stages of Lake Vermont participated in this upwarping, so they also slope southward.

PRELIMINARY DATA.— *Determination of Altitudes.* Altitudes were determined by means of the aneroid barometer and hand level, using such reference points as could be found in Gannett's (1906), Dictionary of altitudes, and on the Burlington and Middlebury topographic sheets.

Glacial Striae. Some idea of the final movements of the glacial ice in the valleys, as a clue to the position of possible ice barriers as parts of shore-lines, seemed highly desirable. For this reason glacial striae were mapped whenever encountered.

[1] Woodworth, 1905, p. 196.

[2] This figure was obtained from calculation based on the profile, Plate 28, of Woodworth's report (1905, p. 226).

The sketch map (Fig. 1.) shows the glacial striae observed around the base of Shefford Mountain. The directions of the striae on the convex north slopes of this isolated mountain are consistent with the idea that the main current of ice at the time the striae were made, was west of the mountain, and was directed southward along the axis of the Champlain valley. In this case the striae on the south (lee) side of the mountain might be crossed in directions, as they are found to be.

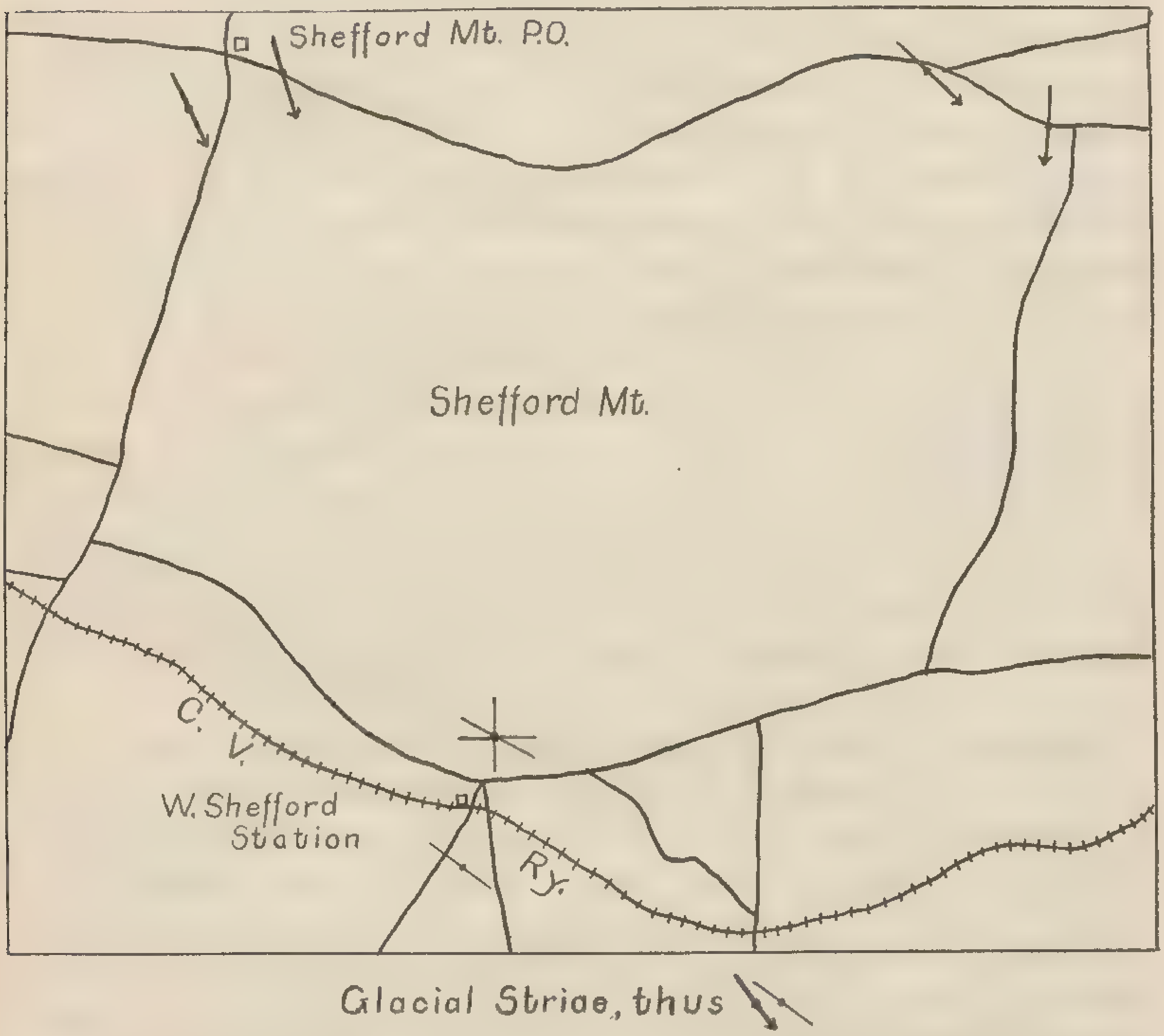

FIG. 1.— Map of glacial striae on the upturned sedimentary rocks around the base of Shefford Mt., Quebec.

In each valley of northwestern Vermont the glacial striae lie nearly parallel with the axis of the valley, whether the valley is longitudinal or transverse. There is, however, a well-marked tendency toward a N. W.–S. E. direction, if the striae are all considered together. This is good evidence that there was a strong movement of ice southward in the Champlain valley after the region just east

of the Green Mountains was nearly free from ice. Taylor (1903, p. 363) finds evidence in the Berkshire Hills that the Green Mountains were an effective barrier to the eastward extension of the ice-front during its retreat from western Massachusetts. For a long time after the main portion of the ice-front began to be confined to the western side of the Green Mountains there were still remnant tongues pushing eastward through the gorges of the Winooski and Lamoille rivers. In the Winooski gorge, near Bolton, roches moutonnées with the plucked sides on the east give conclusive evidence of such movement.[1] The effects of these tongues of ice in the gorges upon the drainage of the valleys east of the Green Mountains will be considered in succeeding paragraphs.

SHORE-LINES IN THE CHAMPLAIN LOWLAND.— It is convenient to begin with the southernmost shore-line features to be considered, and proceed northward. The location of the places mentioned may be found on the map, Plate 2.

Bristol to the Winooski Delta. The Middlebury sheet shows the village of Bristol to be situated on a terrace 600 feet in elevation. A mile west of the village, north of the railroad crossing, there is another terrace at the altitude of 490 feet. From the description which C. H. Hitchcock ('61, vol. 1, p. 131) gives of the surface of these terraces and from their topographic relations, I am led to classify them as deltas and shore-cliffs, and to correlate them with the two highest stages of Lake Vermont, namely: — the Upper Coveville and the Coveville.

Beginning at Bristol and extending north to Hollow Brook, on the east side of the Hogback Mts. there is a longitudinal valley part of which drains northward by Lewis Creek, and part southward by Beaver Brook. The south-draining part of the valley was evenly graded by a filling of water-laid deposits, and was afterward trenched by stream erosion.[2] It is from this valley that the Bristol delta extends. The large amount of water-laid materials in the valley, and the size of the Bristol delta make it evident that no small amount of drainage from the ice coursed through the valley while the delta was building into Lake Vermont. The altitude of the valley deposits makes it seem probable that the process of valley filling began during the latter part of the existence of Lake Albany.

[1] I have not noticed any evidences of local glaciation in northern Vermont. Chalmers ('98, p. 28) and Upham ('95, p. 18) are of the opinion that considerable bodies of ice remained in and east of the Green Mts. after the Champlain valley was free of ice.

[2] It is from the U. S. topographic maps, and the descriptions in Hitchcock's report ('61, vol. 1, p. 131, 141) that I get the facts concerning the deposits from Bristol to Hollow Brook.

When the ice-front had receded so far as to free this valley of ice, it, at the same time, left free the valley of Hollow Brook, which comes into this valley from the east. There is a conspicuous terraced delta at the mouth of the Hollow Brook valley. The top of the highest terrace (665 ft.) is about 20 feet too high for it to be considered contemporaneous with the highest level of the Bristol delta, allowance being made for tilting according to the evidence given by certain shore-line features on the New York side of Lake Champlain. Yet these deltas in Vermont are so much better defined, and so much further north of the Coveville outlets of Lake Vermont, that they probably more accurately define the slope of the Upper Coveville stage than do the shore-line features in New York. Furthermore, if the southward tilting of the shore-lines is due to unloading of the land at the north as the ice-sheet melted, then the first formed shore-lines should slope more than those formed later, provided, of course, that uplift took place at intervals during the unloading, as well as at intervals since.

The Hollow Brook delta is much too large to have been built during the life of Lake Vermont by any stream or ice discharge from the basin which the brook now drains. An explanation of the existence of the delta is found 3 miles up the valley at a divide between Hollow Brook and a stream which flows into the Winooski River. In the water-laid deposits which cover the surface at this divide there is a stream-made trench about 50 feet deep. The floor of the trench is only a few feet higher than the upper level of the delta. This trench is evidently the abandoned outlet of a lake which occupied the lower part of the Winooski basin. As a further confirmation of this idea, I found banded clays dipping west in the valley east of the divide.

Wave lines marked by rounded cobbles and patches of gravel occur at heights of 240 and 265 feet above the sea, near the northern cross-road on the low limestone ridge leading southwestward from Vergennes.[1] In the clayey walls of a drainage ditch one fourth of a mile west of the railroad station at Vergennes at an altitude of 180 feet, I collected ten valves of *Macoma groenlandica.* These marine shells had been transported, I believe, a little way off shore from where they had been living in the shallow water at the base of a limestone hillock. The shells occur about 50 feet below the upper marine limit.

About 4 miles east of Vergennes, Little Otter Creek flows out of a basin about 2 square miles in area through a gap in the western rim of

[1] This ridge was mistaken by Baldwin ('94, p. 172) for an esker.

the basin. The rim at the gap is composed of till. The lower parts of the surface of the gap, between the 260 and 280-foot contours, are strewn with boulders which are evidently a concentration due to the removal of the fine material in which they were enclosed. I recognize here characteristics of wave and current work, rather than those of stream work. I explain this occurrence of boulders, on the hypothesis that when Lake Vermont was lowering, the basin behind the gap held an arm of the lake. When the surface of the lake had fallen so as to nearly expose the low part of the rim of the basin strong scouring began. The last part of the scouring may have been done by tidal currents, for the position of this boulder-bed falls in line with the upper marine limit.

The two small streams next west of this locality flow from narrow swampy areas which meet the spurs of the hills abruptly, as if the swamps were formed by the silting up of bay heads. The swamps are at approximately the level of the bouldery slopes above described (270 feet).

Four miles north of Vergennes, the cross-road leading west from Shellhouse Mountain crosses a boulder-strewn surface at about the 270-foot contour. This wave line follows the contour of the hill northward for 2 miles to a projecting point where the signs of wave action are strongly developed. North of the point there is a delta-filled embayment.

At a lower level (200 feet), and a mile southwest of the line just described, a gravelly ridge having the proper topographic aspects of a barrier beach, extends along the road from Vergennes to Ferrisburg. For 20 feet above this level many of the rock knobs are bare, as if wave washed.

From a well-defined cobble beach 1 mile east of Shelburne Falls, a line of wave action may be followed for 4 miles near the 310-foot contour. Northward, this shore-line becomes less distinct and appears to split up into two lines marked by terraces at elevations of 290 feet and 320 feet, east of Shelburne Bay.

The Winooski Delta. Opposite the north shore of Shelburne Bay, about 2 miles from the last locality mentioned, the 290-foot level is again represented by a terrace. Terraces with broad flats appear below this one, at altitudes of 220 feet and 120 feet. These terraces are all sandy. Comparison of them with terraces on the immediate shores of Lake Champlain, leaves no doubt that they form parts of abandoned shore-lines, the materials of which they are composed being the delta deposits of the Winooski River.

Two miles further east, near the head of Potash Brook, a shore-line appears which may be traced along near the 400-foot contour, for 3 miles. Where this shore-line reaches the hills, pockets of pebbles may be found in many of the small embayments.

From 1 to 3 miles south and southeast of Essex Junction, near the former head of the Winooski delta, terraces at elevations of 400 to 410 feet, and at 500 to 520 feet, overlook the deep trench which the river now occupies. Traces of the 400-foot level may be found on the low hill 2 miles west of the head of Potash Brook.

The Lamoille Delta. Sand flats, rising from 380 feet in altitude near Milton to 395 feet a few miles further up the Lamoille River at East Georgia, and covered in places with drifting dunes and irregular patches of gravel, give general but rather indefinite evidences of a water-level which falls into the plane of the upper marine limit. Making allowance for tilting of this plane between Milton and East Georgia, the water-level which determined the surface of the sand flats must have persisted for a long time. A number of isolated hills rise abruptly out of the delta. Their modifying influence on the distribution of currents probably had much to do with the apparent indefiniteness of the shore-line on the delta. No higher shore-lines were found in this vicinity. It may therefore be inferred that the ice still occupied this part of the Champlain valley when the high terraces of the Winooski delta and of the deltas further south were building into Lake Vermont.

St. Albans Bay. Along the shores of St. Albans Bay narrow terraces and wave lines occur at vertical intervals of from 5 to 20 feet up to the height of 150 feet above the level of the Bay.

The Missisquoi Delta. The lowest terrace of the Missisquoi delta that I studied is the one at an elevation of 305 feet. Two or three feet below the surface of this terrace, in the gravelly top-set beds I found three specimens of a gastropod of an undetermined species, and more than one hundred valves of *Macoma groenlandica.* From this occurrence of marine shells and from occurrences elsewhere in the Champlain district (Woodworth, 1905, p. 208–216) it is clear that marine waters must have stood as high, at least, as this terrace.

The highest point at which sands occur which I can definitely refer to the delta deposits of the Missisquoi River, is at an elevation of 380 feet. This occurrence is near the railroad station at Highgate Centre, about 60 feet below the supposed upper marine limit at this place.

There seems to be no way that the sea could have entered the

Champlain valley except around the eastern borders of the ice as the ice-front receded from its contact with the hills northeast of this part of Vermont. Why well-defined shore-lines do not occur here at what has been considered the position of the highest marine level is an open question.

Upham (1895) and Woodworth (1905, p. 202) have supposed the indefiniteness of the upper marine shore-line on the northwest side of Lake Champlain to be due to a reädvance of the ice into the northern part of the Champlain valley at the close of the upper marine stage, or later. Such an advance would account for the absence of any clearly recognizable beaches above 400 feet in elevation in Vermont, north of St. Albans. The trace of the upper marine shore-line projected northward, crosses the Missisquoi valley near Enosburg Falls, nearly 20 miles east of Lake Champlain, and 15 miles east of the part of the Missisquoi delta where marine shells have been found. Three miles south of Enosburg Falls at the altitude of the upper marine limit (430 feet) the road between East Berkshire and West Enosburg follows a low esker for a mile. The slopes of the esker and of the low ridges east and west of it appear to have been unaffected by wave action. The north end of the esker is buried under the sandy deposits of the terraces of the Missisquoi River. It seems, therefore, that this part of the Missisquoi valley was still occupied by ice at the end of the upper marine stage.

Summary and Conclusions. The east side of Lake Champlain is bordered by abandoned shore-lines referable to several stages of a glacial marginal lake, and to several marine stages. The relations of the various shore-line features which have been found may be seen in Plate 1, on which the relative distances from north to south, and the relative altitudes of the shore-line features are plotted. The delta terraces and beaches along the line L M are so near together and so strongly developed that they appear to belong together, and to mark the stage which was longest, and in which wave action accomplished most. Reference to Woodworth's (1905, p. 226) chart which was constructed in a similar way shows that a line parallel to L M and not more than 20 feet below it represents the upper marine stage for the New York side of Lake Champlain. That these lines are in the same tilted water-plane there can be little doubt. Lines drawn parallel to L M through the points above it are related in the same way to lines on Woodworth's chart. I have, therefore, adopted the names which Woodworth used for these water-levels.

The fact that the shore-lines on the Vermont side of Lake Cham

plain are 20 feet higher than those on the New York side warrants the two conclusions that uplift has been greater on the Vermont side, and that the line of maximum tilting slopes S. S. W.

Shore-lines in the Valleys of the Highland of Northwestern Vermont.

General Statements.— Sections in glacial deposits of several of the valleys in the highlands of northwestern Vermont show beds of well-laminated clay scores of feet in thickness. These are undoubtedly quiet water deposits. In several localities such clays are found to be overlain by till, or are much disturbed at the surface, as if they had been overridden by ice. In other localities gravels having a kame topography overlie clays. It seems, then, that either local or more widespread advances of the ice took place which must have effaced the shore-lines of the bodies of water in which the clays were laid down. For this reason only those structure sections which could be consistently related to existing topographic features of shore-lines have been given weight in the following discussion.

From what has previously been said about the tongues of ice pushing eastward through the water-gaps of the Green Mountains, and from the topographic relations of the valleys east of the mountains, and also from the facts — which are discussed later — concerning the water-laid deposits in the valleys, the following synopsis of the development of drainage in the valleys during the last stages of their occupancy by ice, may give the reader a means of correlating some of the apparently isolated facts which are mentioned later.

If we consider a valley already partly filled with water-laid deposits to be over-ridden by ice which moves up the valley, then, when the ice begins to retreat, a lake may form between the ice and the head of the valley, discharging either down the valley under or around the ice, or across a divide into another valley.

In such a lake outwash from the ice might be spread in broad sand-plains at approximately lake-level around the tongue of the glacier during a period of halting. Such sand-plains might be so effective a barrier as to prevent the water of the lake from falling immediately to a level appropriate to the next halt of the ice. If a complete barrier was not formed the lake would fall to its next level during the withdrawal of the ice. Then a new outwash-plain and other shore-features would develop, giving the former lake basin two sets, if the water-

level did not fall so much as to drain the valley. After successive drops in the level of the lake the head of the valley would be above water and thus subject to river erosion. One of the later stands of the lake might last long enough to allow the inflowing river to grade its course, build a delta and develop flood-plains. While the river was at grade, a large part of the valley filling might be removed by lateral swinging of the river. Thus only flanking terraces would be left to mark the former lake-levels. Let the lake-level to which the river is graded drop again. The river would be permitted to partly consume its former flood-plains and develop new ones.

Now, if, to the history so far outlined, there are added two complications, namely:— that instead of one valley there are three parallel valleys, which during certain periods of the ice retreat were intercommunicating, and that during this glacial history and subsequently there has been tilting of the land on which the records of the lake-levels have been made, then the chief conditions which have obtained in the western Vermont valleys will be recorded.

THE WINOOSKI BASIN.— *Side Valleys.* One of the first lakes to form in front of the ice in the Winooski basin was north of the swampy divide, at an altitude of 990 feet, between the Dog River which is one of the southern tributaries of the Winooski River, and the Third Branch of the White River, which is tributary to the Connecticut River.

Extending north from the divide at Roxbury, there is a sand-plain which rises northward to a height of 20 feet above the divide, where it joins an esker about one third of a mile long. On the east side of the head of the sand-plain an ice-block hole has a delicately marked shore-line about its rim. Such a line may be ascribed to lake ice action along the shore, rather than to waves.

A massive sand terrace which appears 2 miles north of Roxbury on the east side of the railroad at an elevation of 975 feet was probably built in a marginal lake.

Three deltas, further down the Dog River valley, in the vicinity of Northfield, at an elevation of 940 feet, were all possibly built into one lake. One delta is at the mouth of a tributary entering the Dog River from Northfield Centre, another is east of the Northfield railroad station at the mouth of a small brook, and the other is one and one half miles south of Northfield on the east side of the river.

Two and one-half miles south of Northfield terraces, which are gravelly, occur on the sides of the valley at heights of 845, 830, 820 feet above the sea. They were probably cut by streams marginal to

stagnant ice. Terraces due to three successive periods of grading of the present stream are found below the gravel terraces. The upper one, at an elevation of 775 feet, is much broader than the rest, and dies out further down the valley. Inasmuch as I found no barriers down the valley to account for these periods of grading, I have supposed that they were caused by successive lowerings of a lake which formed the local base-levels. Evidence of a lake at this 775-foot level is found northward, 3 miles further down the valley, where a delta-like deposit occurs at the mouth of Jones Brook. The upper terrace shown in Plate 3, fig. 1, is also at this elevation. It is across the river from, and about half a mile north of Jones Brook and the village of Northfield. The lower terraces shown in the view are of the same origin as those described at the beginning of this paragraph. Similar terraces occur still further north.

In the north-south valley next east of the Dog River valley a lake formed north of the 890-foot divide near Williamstown. This divide is in a swamp which drains both northward into the Winooski River, and southward through the Second Branch of the White River into the Connecticut River. Immediately north of the divide the valley floor is occupied by a lakelet about one half a mile long, probably an ice-block basin, and by a small esker with a bordering belt of kames. A little further north the stream draining the pond falls over a 20-foot ledge into a swamp.

South of the divide there are two other small lakelets in rock basins. Beyond them, southward, the valley floor has been swept nearly clear of glacial materials by the temporary discharge of the glacial lake north of the divide. Still further south the flat valley floor gives place to a narrow postglacial gorge with cascades. Below the cascades the gorge widens considerably and is floored with alluvial deposits over which the small stream meanders. The excavation of this part of the gorge was evidently done by a larger stream than the present one, for the present stream is aggrading here. Part of the excavation is probably preglacial, most of the remainder was done by a glacial stream while an ice-tongue still projected south of the divide. Only a small part seems to have been done by the water flowing from the glacial lake behind the divide, for erosion has not been great near the divide and the small lakes in the path of such drainage have not been filled.

The ice-front stood for some time about 3 miles north of the divide, discharging debris into a lake which occupied the site of Williamstown. A section about 20 feet in depth near the railroad station shows by

the crossbedding that the discharge from the ice was southward, but the top-set beds of this delta were not found at a height greater than 20 feet below the divide which held the lake in. This fact testifies to the early establishment of drainage down the valleys around the ice. To have allowed this the ice must have been in large part stagnant.

The divide at Williamstown is the lowest one between the Lake Champlain drainage and that of the Connecticut River. It is about 400 feet higher than the highest stage of Lake Vermont. Therefore, Lake Vermont never had an outlet into the Connecticut River.

Between Williamstown and the main valley of the Winooski River the railroad traverses an area of typical kame topography of which the many unfilled basins at an altitude of about 760 feet are evidence that lacustrine conditions did not prevail above this elevation after the valley was free of ice.

At the junction of this side valley with the main valley there are, however, broad flats underlain by horizontal fine sands at a height of 745 feet above the sea. A mile up the side valley a narrow embayment is fringed with distinct marks of a shore-line at an altitude of 750 feet.

The only one of the valleys tributary to the Winooski on the north which I visited, is the Waterbury valley. This valley has been referred to as the most typical of the longitudinal valleys. It lies east of Mt. Mansfield. At the mouth of this valley, as well as in the main valley of the Winooski, terraces composed almost wholly of clay rise nearly 100 feet above the river, and over 500 feet above the sea. Clays are found also up the Waterbury valley at an altitude of over 700 feet.

The divide on the valley floor between the Waterbury valley and the valley of Joe's Brook — which slopes northward — is only 740 [1] feet above the sea. The surface at the divide is wholly made up of water-laid gravel and sand. The aspect of the eastern part of the divide is shown in Plate 3, fig. 2. Here it is seen as two well-marked terraces about 15 feet high and 400 feet wide, trending squarely across the valley. The terraces are about three fourths of a mile long, and although they appear horizontal, they slope westward along their trend about 60 feet per mile. At their eastern ends they grade into kame terraces which border the valley for miles, at their western ends they die out in a broad sandy plain. The eastern part of the upper terrace

[1] Four barometric determinations from Waterbury (427 feet) gave a mean of 690 feet for the altitude of Stowe (hotel steps).

is crossed obliquely by inconspicuous terraces which radiate from its southeastern margin. A small stream enters the valley near this point. The terraces face a nearly level valley floor below which the small stream and the Waterbury River are entrenched a few feet.

Northward from the edge of the highest terrace the gravels become hummocky, a few kame kettles appear, and near the 700-foot level clay becomes conspicuous, even on the knolls. The clay is clearly a lacustrine deposit.

It is apparent then, that stagnant ice was present during the deposition of the gravels, and that the valley north of the divide was occupied by a lake after the disappearance of the ice.

Although my studies were not detailed enough to give data for a thoroughly satisfactory explanation of the origin of the terraces, I feel sure that they represent approximately the levels at which lake waters stood, submerging the lowest part of the divide.[1] The altitudes of beaches near Montpelier (735 feet) and near Morrisville in the Lamoille valley a few miles north of this divide (760 feet), are further evidence that water stood high enough to over-top the divide. I have called this water body Lake Mansfield because of its topographic relation to Mt. Mansfield.

—. — *Main Valley.* The upper Winooski valley between Plainfield and Montpelier is deeply filled with water-laid deposits which rise to an altitude of 750 feet.[2]

On Seminary Hill in Montpelier a section exposes the following sequence of deposits. Upon a thick base of clay there rests 6 feet of horizontally bedded fine sand. The sand is followed by 4 feet of gravel in thin broad lenses. The contact of the gravel and sand is so nearly a plane that I believe the gravel has been dragged from a beach by wave-currents, over off-shore sands, during the lowering of the water-surface under which the sand was laid down. The slope of the gravelly surface is a few feet per hundred upward from this locality to the hills, the line of meeting being about 675 [3] feet above the sea. A level at a corresponding altitude, and gravel-

[1] Either the terraces were cut and leveled by wave action — which seems improbable because they slope — or they were made by a stream which was confined by ice walls on both sides. Evidence of an ice wall on the north side is at hand, but such evidence on the south side I did not notice. The brook entering the valley at the east end of the terraces, acting with water from the melting ice, is a possible terrace-making agent.

[2] Clay and cross-bedded gravel dipping east were noted in a cut west of the viaduct in Plainfield, at an elevation of 750 feet.

[3] The altitudes in the vicinity of Montpelier are referred to Montpelier Junction (522 feet). The railway stations in Montpelier are not more than 5 feet lower.

covered, occurs east of Washington St. in the city of Barre. Pebbly ridges crossing this flat near Main St., I have considered to be beach lines.[1]

The Winooski valley westward from the Green Mountains has an upper terrace level at 565 feet above the sea. This is best represented northwest of the village of Richmond. It is found also on the south side of the valley extending east of Richmond about 3 miles to the mouth of the Huntington River, which comes into the Winooski River from the south. This set of terraces corresponds to the Coveville stage Lake Vermont.

West of Richmond there is a terrace level along the 500-foot contour aggregating several square miles in area. This has already been referred to as one of the upper levels of the Winooski delta in Lake Vermont. All the terraces in the vicinity of Richmond below an altitude of 500 feet must be stream terraces, unless there was a rise in the level of Lake Vermont after the river had trenched its delta and developed flood-plains accordant with the lake-level.

Two and one-half miles south of Richmond, near Owl's Head hill, banded clays occur in roadside cuts at an altitude of 645 feet. East of the hill a deeply dissected sand-plain attains the observed elevation of 650 feet. Outwash from the ice is the only probable source of the materials in these deposits. This sand-plain must have been built into a lake tributary to Lake Vermont during a part of the Upper Coveville stage of Lake Vermont. The presence of the ice as far south as this locality at this time, supports Woodworth's belief that at the time of the Upper Coveville stage the ice impinged against the mountain side as far south as Port Kent, New York.

THE LAMOILLE BASIN.— *The Main Valley.* I traversed the Lamoille valley from Milton near its mouth, eastward to Greensborobend near its source.

The most elevated sections which gave evidence of origin in standing water are well up the river, in the village of Hardwick. Near the railroad station at this place at an altitude of 895 feet, cross-bedded sands enclose numerous clods of stony till. East of the village at an elevation of 1055 feet a large body of gravel, apparently of proglacial-delta type, forms a flat surface half a mile wide. The level of the water in which this deposit was made was high enough to have extended northward into as much of the Lake Memphremagog valley as may have been free from ice at that time. Certain high-level

[1] Contorted clays under this terrace, I have taken as an evidence of reädvance of the ice.

terraces in that valley Hitchcock[1] has correlated with stages of a glacial lake which he has called Glacial Lake Memphremagog.

If the amount of tilting has been correctly measured the lake at Hardwick at the 1055-foot level could not have drained into the Connecticut River, for the lowest point between the basins of the Connecticut River and the St. Lawrence River was then higher than this lake. (The point is near Williamstown at 890 feet). The drainage was probably southwestward along the ice-front.

A few miles further down the river, one mile west of Wolcott, an exposed section of a delta shows fore-set beds dipping south, and top-set beds of thin lenses of gravel. At the level of the top of this section, 800 feet in elevation, there is a delta-like deposit at the cemetery northeast of the village, and broad terraces at the mouth of Wild Brook, 2 miles west of the village. The water-body standing at this level could not have drained northward into Lake Memphremagog. Because it was confined to the Lamoille valley it seems appropriate to call this body of water Lake Lamoille.

Still further down the river near Morrisville, the Lamoille valley widens broadly where it is met on the south by the Joe's Brook valley. Sandy plains with small dunes and gravelly ridges cover an area of several square miles. On the hill slopes between Joe's Brook and the Lamoille River irregular terrace-like forms cross the Elmore road at an elevation of 950 feet and lower. At 790 feet, 760 feet, and 725 feet above the sea, parallel gravelly ridges from 1 to 3 feet high, each below a terrace cliff, and separated from it by a slight depression, border the valley southeast of Morrisville. The terrace cliffs face the valley. The ridge below the cliff at the altitude of 760 feet has an exposed cross-section showing the gravel of which it is composed to be distinctly cross-bedded, the dip of the beds being toward the adjacent terrace cliff. The topography and structure of this gravel ridge, and the topography of the adjacent country all support the idea that the terrace cliffs here are wave-cut, and that the low ridges below them are barrier beaches. Moreover, a water-level at about the altitude of the highest of these terraces is necessary to account for the clays, and the northerly drainage, of the valley of Joe's Brook.

The larger part of the floor of the valley about Morrisville is very evenly filled to an altitude of about 660 feet.[2] The river is deeply

[1] C. H. Hitchcock, High level gravels in New England. Bull. Geol. Soc. Amer., 1894, vol. 6, p. 460.

[2] Large masses of highly contorted clays may be seen in the eastern part of the village at about this elevation.

trenched below the surface of this filling. A hundred acres or more of the surface of the northern portion of this plain consists of such loose gravel that there is not sufficient water retained at the surface to support any noticeable vegetation except mats of the lichen, *Cladonia rangiferina*, and a few trailing blackberry bushes. This deposit is near the head of what must have been a glacial sand-plain, for no other source of such material seems possible. At Hyde Park, 3 miles down the river from Morrisville, the plains above the river are at this altitude (660 feet). In fact, the upper terrace level for the next 15 miles down stream, as observed in several places, is about 650 feet above the sea. The one farthest west is on the south side of the river at Jeffersonville. An eastern spur of this terrace is separated from the adjacent hill slopes by a depression which is strewn with angular boulders. The ice must therefore have been present in the depression while the terrace was forming.

This terrace level, reaching from Morrisville to Jeffersonville, could not have been made before the Coveville stage of Lake Vermont for this stage of the lake attained an altitude of 650 feet at Jeffersonville. That much of the material of the terraces was deposited directly from the ice in deep water is shown by irregular cross-bedding in cuts near Jeffersonville and near the railroad station at Johnson, and also by regularly south-dipping gravel beds midway between Hyde Park and Johnson. The presence of ice during the deposition makes it probable that several lakes at approximately the same level occupied the valley, discharging from one to another westward, through broad channels, rather than that a single body of water extended the entire length of the part of the valley in which the terrace was observed.

A terrace at the 620-foot level, having much the same origin as the one at the 650-foot level, extends interruptedly from Hyde Park to Jeffersonville. At this level, the spur of the terrace at Jeffersonville, mentioned in the preceding paragraph, is covered to a depth of nearly 2 feet with a concentration of pebbles, a large part of which are from 1 to 4 inches in diameter. The valley here, at the time of this terracing, seems to have been free enough of ice to permit considerable wave-cutting on this spur.

For the 8 miles next west from Jeffersonville the Lamoille valley is floored with water-laid materials which are dune covered in many places. Terraces at observed elevations of 535 to 550 feet, and 485 to 500 feet were seen on both sides of the valley. Numerous sections indicate that, at least locally, lacustrine and fluviatile conditions have alternated more than once since the filling of the valley began.

—. — *The Side Valleys.* Fifteen miles east of Lake Champlain Brown's River enters the Lamoille River from the south. In the eastern junction angle between the streams, sand terraces reach an altitude of about 540 feet. Terraces are absent from the north side of the Lamoille River in this vicinity on account of the presence of ice there during the building of the terraces on the south side. Brown's River had no part in this terrace building for it drains an unfilled basin of which the terrace deposits are the northern rim. The Brown's River valley, during the Wood Creek stage of Lake Vermont, was submerged by an arm of the lake at least 100 feet. Into the north end of the valley at this time sediments collected from the ice and from the Lamoille River; into the south end the Winooski delta encroached; into the middle, only a little sediment from small side streams, and clay from the ice, found their way. Corresponding to this level of Lake Vermont, beaches were formed northeast of the northward bend of the river at an elevation of 510 feet, and 3 miles north on the east side of the valley, wave-washed slopes at about 515 feet.

When Lake Vermont began falling from its Wood Creek stage the Lamoille River still drained through the lake in the Brown's River valley. Its old channel across the Winooski delta is at an altitude of 490 feet. Very soon, however, the ice in the lower Lamoille valley gave way, allowing the Lamoille River to occupy its preglacial channel. The lake in the Brown's River valley then began draining into the Lamoille River.

From near Jeffersonville a longitudinal valley extends northward, joining the Lamoille valley and the Missisquoi valley. The swampy divide on the floor of the longitudinal valley attains an altitude of about 450 feet. South of the divide kames and outwash gravels rise to an elevation of 550 feet. Southwest of the divide laminated clays occur 30 feet above the divide. The clays are overlain by gravels which form an ice-block basin south of the cross-road leading to North Cambridge. Here the clays dip south. These relations are explainable on the hypothesis that the clays were laid down in a lake standing at an elevation of 580 feet or more, and that an advance of the ice over them left a stranded ice-block.

THE MISSISQUOI BASIN.— *The Side Valleys.* The northern part of the longitudinal valley just described, also contains glacial outwash gravel. At Sheldon the gravels attain a height of 450 feet above the sea, and at the divide between Sheldon Springs and Green's Corners, a height of 460 feet. The latter deposit is irregularly cross-bedded and contains scattered boulders reaching four feet in diameter.

Half a mile east of Green's Corners, stratified clay with a thin capping of gravel was found at an altitude of about 440 feet. This clay is high enough to have been laid down in Lake Vermont shortly before the marine invasion, but if it was so deposited the deposition took place prior to the last appearance of the ice in the vicinity, for west of Green's Corners a till plain forms the valley floor a hundred feet below the altitude of the clay.

About 8 miles west of the Green Mountains and midway between the Lamoille River and the Missisquoi River, in another longitudinal valley, a sand-plain nearly a square mile in area has an altitude of about 600 feet.[1] The village of Bakersfield is situated upon it. A mile northwest of Bakersfield and at the same level there is a small trenched proglacial delta with an ice-contact on the north side. Only a few rods west of the little delta, a well-defined esker, extending northward, ends abruptly in a transverse valley. No recognizable relation exists between the sand-plain and the esker, though the esker is more than a mile long, and in places more than 100 feet high. Half a mile southeast of Bakersfield the sand-plain gives place to kames amongst which two lakelets fringed with sphagnum bogs still remain.

Two and a half miles west of Bakersfield on the road to East Fairfield, banded clay which contains scattered boulders as large as a foot in diameter was found in a cut at an altitude of about 500 feet. The boulders were probably dropped by floating ice. It is very probable that the waters of Third Lake Lamoille extended far enough north to have determined the level of the Bakersfield sand-plain and other lacustrine deposits in the vicinity.

—. — *The Main Valley.* The uppermost terrace along the Missisquoi River north of Bakersfield and Sheldon is so gently sloping down the valley that, whether it is entirely due to stream aggradation or to a combination of processes such as have already been discussed, it can be but a few feet above the level of a body of water into which the river emptied at the time the terrace was forming. An ice barrier at the mouth of the valley, or an arm of the sea at a stage immediately succeeding the upper marine stage may have determined the altitude (430 feet) of this terrace.

Summary and Conclusions.— The main valleys of northwestern Vermont drain westward. Owing to their opening into the low Champlain valley which largely controlled the direction of retreat of

[1] This figure in based upon several barometric determinations from Swanton as a base. The figures for the altitudes of Sheldon and E. Fairfield are interchanged in Gannett's Dictionary.

the Wisconsin ice from the region, the heads of the valleys were first freed of ice. Marginal lakes then collected between the ice-front and the divides. The first lakes to form were at the head branches of the Winooski River. Each of them for a brief time spilled over into the Connecticut River drainage. The last marginal lake in the Winooski valley to abandon the Connecticut River drainage was a small one north of the 890-foot divide near Williamstown. This happened before the lakes in the branch valleys had become confluent, and from this time drainage took place beneath or around the ice into the Champlain valley. As the ice withdrew further and the lakes coalesced the First Lake Winooski stages were entered upon. (Plate 2.)

By this time, in the Lamoille valley, a similar lake was growing. At an early stage it is probable that it drained northward through the Lake Memphremagog basin. The stages preceding this probable stage have been called First Lake Lamoille, and those immediately succeeding, Second Lake Lamoille.

As soon as the ice no longer obstructed the valleys east of the Green Mountains, First Lake Winooski and Second Lake Lamoille met in the longitudinal valley east of Mt. Mansfield, thus introducing the Lake Mansfield stage.

Lake Mansfield came to an end when its level dropped enough to cause a division between the waters that occupied the Lamoille valley, and those which occupied the Winooski valley. This division brought into existence the Second Lake Winooski and the Third Lake Lamoille stages.

With further retreat of the ice-tongue which occupied the western part of the Winooski valley, a strong discharge of glacial waters took place through an arm of Lake Winooski which stood high enough to drain across the divide east of Hollow Brook.

Subglacial communication was soon after established between Lake Winooski and Lake Vermont, and then Lake Winooski dropped to the level of and coalesced with Lake Vermont.

At this time the ice still obstructed the Lamoille valley. It was not until Lake Vermont had fallen to its Wood Creek stage that Lake Lamoille became directly confluent with it, first through the Brown's River valley, and later through the present valley.

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PLATE 1.

North-south profile of shore lines along the eastern side of Lake Champlain.

C–D — Coveville stage of Lake Vermont.

E–F — Wood Creek stage of Lake Vermont.

L–M — Upper marine stage.

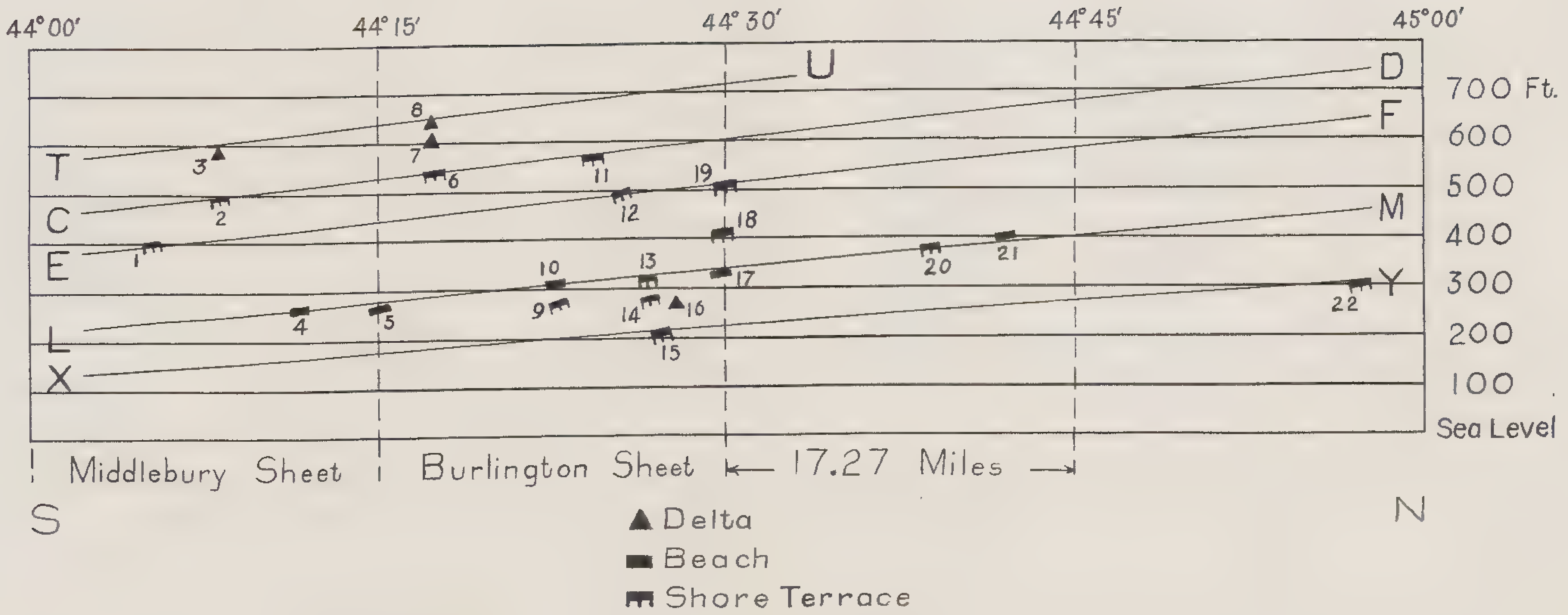
T–U — Upper Coveville stage of Lake Vermont.

X–Y — The two wide terraces through which the line X–Y is drawn are the most strongly developed ones next below the upper marine level. For this reason they have been considered contemporaneous. The gentler tilt of the line thus drawn is consistent with the idea that it represents a marine stage after uplift had begun.

1. Terrace at New Haven Mills (see Middlebury sheet), 390 ft.
2. Terrace at Bristol, 490 ft.
3. Delta at Bristol, 600 ft.
4. Beach near Little Otter Creek, 270 ft.
5. Beach near North Ferrisburg, 270 ft.
6. A narrow terrace on the south side of the Hollow Brook delta, 540 ft.
7. The broadest level of the Hollow Brook delta, 625 ft.
8. The highest level of the Hollow Brook delta, 665 ft.
9. Terrace near Shelburne, 280 ft.
10. Beaches east of Shelburne Falls, 310 ft.
11. Terraces about Richmond, 570 ft.
12. Terraces west of Richmond, 500 ft.
13. Terraces east of Shelburne Bay, 310 ft.
14. Terraces east of Shelburne Bay, 290 ft.
15. Terrace near the mouth of Potash Brook, 290 ft.
16. Delta near the mouth of Potash Brook, 220 ft.
17. Strong beach lines south of Essex Junction and east of Muddy Brook, 340 ft.

18, 19. Terraces east of Essex Junction, 410 ft., 510 ft.

20. Terraced sand flats west of Milton, 380 ft.
21. Terraced sand flats south of East Georgia, 395 ft.
22. Terrace on the Missisquoi delta, near Highgate Centre, containing marine shells, 305 ft.



44° 00′
44° 15′
44° 30′
44° 45′
45° 00′
U
D
F
T
C
E
M
L
Y
X
700 Ft.
600
500
400
300
200
100
Sea Level
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
Middlebury Sheet
Burlington Sheet
17.27 Miles
S
N
Delta
Beach
Shore Terrace

PLATE 2.

A. Sketch map of northwestern Vermont. Key to abbreviations.

B.— Bakersfield.
Ba.— Barre.
Br.— Bristol.
Bu.— Burlington.
E.— Essex Junction.
E. F.— Enosburg Falls.
E. G.— East Georgia.
F.— Ferrisburg.
G. C.— Greens Corners.
H.— Highgate Centre.
Ha.— Hardwick.
H. Bk.— Hollow Brook.
J.— Jeffersonville.
Jo.— Johnson.
Lan. R.— Lamoille River.
L. Mem.— Lake Memphremagog.
L. Ot. Cr.— Little Otter Creek.
M.— Milton.
Mis. R.— Missisquoi River.
Mo.— Morrisville.
Mp.— Montpelier.
Mt. M.— Mt. Mansfield.
N.— Northfield.
P.— Plainfield.
R.— Roxbury.
Ri.— Richmond.
S.— Stowe.
S. F.— Shelburne Falls.
St. A.— St. Albans.
V.— Vergennes.
N.— Williamstown.
Wa.— Waterbury.
W. Bk.— Wild Brook.
W. E.— West Enosburg.
Win. R.— Winooski River.
Wo.— Wolcott.

B–F.— Diagrammatic maps of certain lake stages in northwestern Vermont.

B. a. — A marginal lake south of Northfield (945 ft.).

b. — Lake Williamstown (890 ft.), discharging into the Connecticut River.

C. a. — Second Lake Lamoille just after falling below the level of the divide at Eligo Pond (900 ft.).

b. — First Lake Winooski at a stage represented by an altitude of about 745 feet at Plainfield.

D. a. — Lake Mansfield. The terraces and beaches in the vicinity of Montpelier at 650 to 675 feet in altitude and those near Morrisville at 760 to 790 correspond to the level of this lake. Ice in the vicinity of Richmond held the water of Lake Mansfield somewhat higher than the level of Lake Vermont or the last stage of Lake Albany (b.)

E. a. — Third Lake Lamoille (650 ft.) during a part of the Coveville stage of Lake Vermont (b).

F. — Wood Creek stage of Lake Vermont. The lines between the question marks in the last three diagrams represent hypothetical ice borders.

A
B
C
D
E
F
QUEBEC
NEW YORK
L. Champlain
L. Mem.
H.
Mis. R.
E.F.
G.C.
Sh.
W.E.
St.A.
B.
E.G.
M.
Lam. R.
J.
Jo.
Mp.M.
Mo.
Wo.
Ha.
Bu.
E.
Win. R.
S.
Ri.
S.F.
Wa.
Mp.
P.
Bo.
N.
R.
W.
F.
V.
Br.
500
1000
1500
2000
10 Miles
ICE FRONT
a
b
?

PLATE 3.

FIG. 1.— Terraces on the Dog River one mile north of Northfield, Vt.

FIG. 2.— Terraces at the divide east of Mt. Mansfield between Stowe and Morrisville, Vt.

1.

2.

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